The effect of postural threat on the scaling of anticipatory postural adjustments in healthy young adults

Angel Phanthanourak, BSc

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Brock University

St. Catharines, Ontario

Dedication

For my loving parents.

Abstract

Earlier and larger anticipatory postural adjustments (APAs) are generated with increasingly destabilizing movements, such as pulling more forcefully onto a handle, to prevent a loss of balance. The purpose of this study was to determine the influence of postural threat on the ability to scale the magnitude and timing of APAs to increasing amounts of force exertion. Nineteen participants (7 F, 24 ± 2 y, 69.6 ± 9.9 kg, 1.7 ± 0.1 m) pulled on a handle while standing on a surface that was either stationary (No Threat) or that could translate in the medio-lateral direction (Threat). For both conditions, participants completed 36 handle pulls that ranged between 50% and 100% of the participant's maximal force exertion. For each handle pull trial, APAs were quantified from center of pressure (COP) recordings and electromyographic (EMG) activity of the posterior leg muscles. Results indicated that participants were more physiologically aroused ($p=0.013$), anxious ($p<0.001$), and fearful of falling ($p<0.001$) during the Threat compared to No Threat condition. This threat response was associated with a reduced ability for participants to scale the magnitude of APAs to the amount of force exertion. This was evidenced by 22% shallower regression lines between COP displacement at pulling onset and force exertion during the Threat compared to the No Threat condition ($p=0.019$). The scaling of APA timing was affected by threat to a lesser extent, as only the regression lines between medial gastrocnemius EMG onset and force exertion were shallower (37%) during the Threat compared to the No Threat condition ($p=0.049$). Regression lines for COP onset and all other posterior leg EMG amplitudes and onsets to force exertion were not different between conditions. These findings suggest that

increased anxiety and fear of falling may contribute to the declines in APA scaling demonstrated by individuals at an increased fall risk (e.g., older adults).

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

A-P	anterioposterior
APA	anticipatory postural adjustment
BOS	base of support
BB	biceps brachii
COM	centre of mass
COP	centre of pressure
CPA	compensatory postural adjustment
EDA	electrodermal activity
EMG	electromyographic
HAM	hamstring
Fmax	maximum pulling force
MG	medial gastrocnemius
M-L	mediolateral
PD	posterior deltoid
SOL	soleus
TA	tibialis anterior

1.0 Literature Review

1.1 Postural Control in Humans

Postural control is the act of preserving a state of balance during a static or dynamic movement (Pollock, Durward, Rowe & Paul, 2000). While posture is considered to involve the orientation adopted by the head, trunk, and limbs of the body (e.g., sitting, bipedal stance, or single-leg stance), balance is defined as how stable the body is while in a particular orientation (Pollock et al., 2000). An individual is considered to be balanced when the projection of their body centre of mass (COM) in the transverse plane is located within the limits of their base of support (BOS), and unbalanced and falling when their COM is outside of their BOS (Pollock et al., 2000). The COM is the weighted average of all segments of the body represented by a single point on a coordinate system, and the BOS encompasses areas where the individual is in contact with the support surface (Johansson, Magnusson & Akesson, 1988). The farther the COM can displace before its gravitational projection surpasses the boundary of the BOS and become unbalanced, the more stable the body (Pollock et al., 2000). Thus, during quiet standing an individual can increase their stability by increasing the size of their BOS, lowering their COM, and having their COM more centralized within their BOS (Pollock et al., 2000).

Successful postural control requires the maintenance or restoration of a state of balance in response to externally- or internally-evoked perturbations to posture (Massion, 1992). Externally-evoked perturbations or external disturbances are conditions outside of the body that induce deviation from an intended posture (Blickhan, Ernst, Koch & Müller, 2013). This can include situations such as experiencing a trip or slip, or receiving a push or pull to the body (Pollock et al., 2000). Internally-evoked perturbations or internal disturbances to posture are generated by the execution of voluntary movement or the movement between postures (Massion, 1992; Pollock et al., 2000). For example, when performing a rapid, isometric handle pull, similar to opening a heavy door or drawer, reaction forces are exerted from the handle to the body (Weeks, 1994; Massion, 1992; Elble & Leffler, 2000). Based on the inverted pendulum model, the reaction forces exerted on the body will produce a torque at the ankle that will act to propel the COM towards the handle, leading to a disturbance to posture (Elble & Leffler, 2000). Fortunately, there are two postural control strategies that can minimize the displacement of the COM due to external or internal disturbances to balance.

The first postural control strategy is known as a reactive postural strategy or compensatory postural adjustment (CPA). This involves muscle responses or changes to posture following an expected or unexpected postural disturbance of internal or external origin (Pollock et al., 2000). CPAs include fixed-support strategies, such as swaying about the ankle following a push, that centralize the COM projection within the BOS without changing the BOS (Pollock et al., 2000). CPAs may also consist of change-in-support strategies, such as taking a step following a push, that capture the COM within the adapted BOS limits (Pollock et al., 2000).

The second postural control strategy is known as a predictive postural strategy or anticipatory postural adjustment (APA). This serves to increase muscle activity and displace the centre of pressure (COP) in expectation of an upcoming internal or external disturbance to balance (Massion, 1992; Pollock et al., 2000). The displacement of the COP acts to reign in the COM within the BOS. For example, the APA associated with the isometric handle pull results in an ankle torque that opposes the torque generated by the handle that destabilizes the COM (Elble & Leffler, 2000). The ankle torque generated by the postural muscle activation causes the COP to move between the COM and the handle to propel the COM away from the handle to maximize stability or distance of the COM from the BOS. Although CPAs are also critical for postural control, the focus of this thesis will be on postural strategies executed in anticipation of internally-evoked perturbations to posture.

1.2 Anticipatory Postural Control

1.2.1 Introduction to Anticipatory Postural Adjustments

Anticipatory postural adjustments are increases in muscle activity and displacements of the COP that occur in expectation of a predicted perturbation to balance (Massion, 1992; Pollock et al., 2000). One purpose of an APA is to assist with the initiation of voluntary movement or movement between postures by impairing the initial posture (Massion, 1992; Pollock et al., 2000). For example, when rising to toes from quiet stance, the movement is preceded by activation of the tibialis anterior (TA) to displace the COP backwards by 2-6 cm (i.e., the APA) (Adkin, Frank, Carpenter & Peysar, 2002; Phanthanourak, Cleworth, Carpenter, Adkin & Tokuno, 2016). This shift in COP propels the COM forward so that the individual can push their body up and over their toes. Approximately 170-400 ms after TA onset, the soleus (SOL) is activated in order to move the COP ahead of the COM, so that forward movement of the COM is slowed and the COM can assume its new elevated position over the toes (Adkin et al., 2002; Kasai & Kawai, 1994; Phanthanourak et al., 2016). The muscle activation pattern associated with this APA acting in the anterioposterior (A-P) direction is responsible for destabilizing the COM in the direction of the projected movement to assist with initiation.

The second purpose of an APA is to proactively counteract the destabilizing forces expected from the impending voluntary movement (Massion, 1992; Pollock et al., 2000). For example, during step initiation there is an APA that acts in the mediolateral (M-L) direction. This M-L APA consists of an increase in hip abductor activity and displacement of the COP towards the swing leg, which propels the COM towards the stance foot (Gendre, Yiou, Gélat, Honeine & Deroche, 2016; Yiou, Deroche, Do & Woodman, 2011). Similarly, the APA that precedes a rapid shoulder abduction of the right arm consists of increased hip abductor activity and a rightward COP displacement. The rightward displacement of the COP propels the COM to start farther from the right edge of the BOS (Balasubramaniam & Wing, 2002; Belenkii, Gurfinkel & Paltsev, 1967; Friedli, Cohen, Hallett, Stanhope & Simon, 1988). Thus, the APA ensures that the COM maintains a safe distance from the BOS limits following initiation of the arm raise and consequently, promotes stability.

Similar to an arm raise task, the APA prior to pushing or pulling on a fixed handle generates an ankle torque to pre-emptively counteract the destabilizing torque associated with the reaction forces from the handle (Figure 1) (Bleuse, Cassim, Blatt, Labyt, Derambure, Guieu & Defebvre, 2006; Elble & Leffler, 2000; Lee, Chen & Aruin, 2015; Lee, Michaels & Pai, 1990; Weeks, 1994). When activating the triceps brachii to push a fixed handle away from the body, the resulting reaction force acting on the body will cause the COM to approach the posterior border of the BOS (Cordo & Nashner, 1982; Dietz, Kowalewski, Nakazawa & Colombo, 2000; Elble & Leffler, 2000). The opposite effects are observed during a handle pull task. Activation of the biceps brachii (BB) and posterior deltoid (PD) to pull a handle towards the body causes the COM to approach the anterior edge of the individual's BOS (Bleuse et al., 2006; Elble & Leffler, 2000). The associated APA, which prior to a handle push task consists of TA activation and backwards displacement of the COP, safely maximizes the distance of the gravitational projection of the COM from the BOS limit that the COM is predicted to approach at the onset of the task (Cordo & Nashner, 1982; Dietz et al., 2000; Elble & Leffler, 2000; Lee et al., 2015).

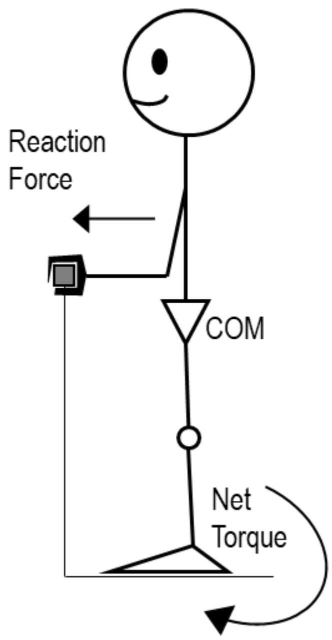


Figure 1. A schematic diagram of an individual pulling onto a rigid handle bar adapted from Elble & Leffler (2000). Pushing or pulling onto a handle produces a reaction force onto the body COM. The reaction force produces a destabilizing torque at the ankle joint. However, the generation of an APA can pre-emptively counteract the destabilizing torque. Thus, the net ankle torque is reflective of the destabilizing torque, as well as a counteracting torque generated by an APA (Elble & Leffler, 2000).

In the case of a handle pull movement, which was performed by the participants of this thesis, individuals first activate the triceps surae and hamstring (HAM) muscles, causing a ~3.5 cm forward displacement of the COP (Cordo & Nashner, 1982; Dietz et al., 2000; Lee et al., 1990; Petersen, Rosenberg, Petersen & Nielsen, 2009; Weeks, 1994). This APA displaces the COM backwards and away from the handle prior to pulling onset. Approximately 40-560 ms following the onset of the APA, the prime movers responsible for the handle pull, such as the BB and/or PD muscles, are activated (Figure 2) (Cordo & Nashner, 1982; Dietz et al., 2000; Lee et al., 1990). The activation of the BB and/or PD muscles causes an increase in the amount of force being exerted onto the handle (Figure 2), which is deemed the pulling force onset. The time from APA onset to pulling force onset has been found to range from ~150-780 ms (Cordo & Nashner, 1982; Dietz et al., 2000; Lee et al., 1990).

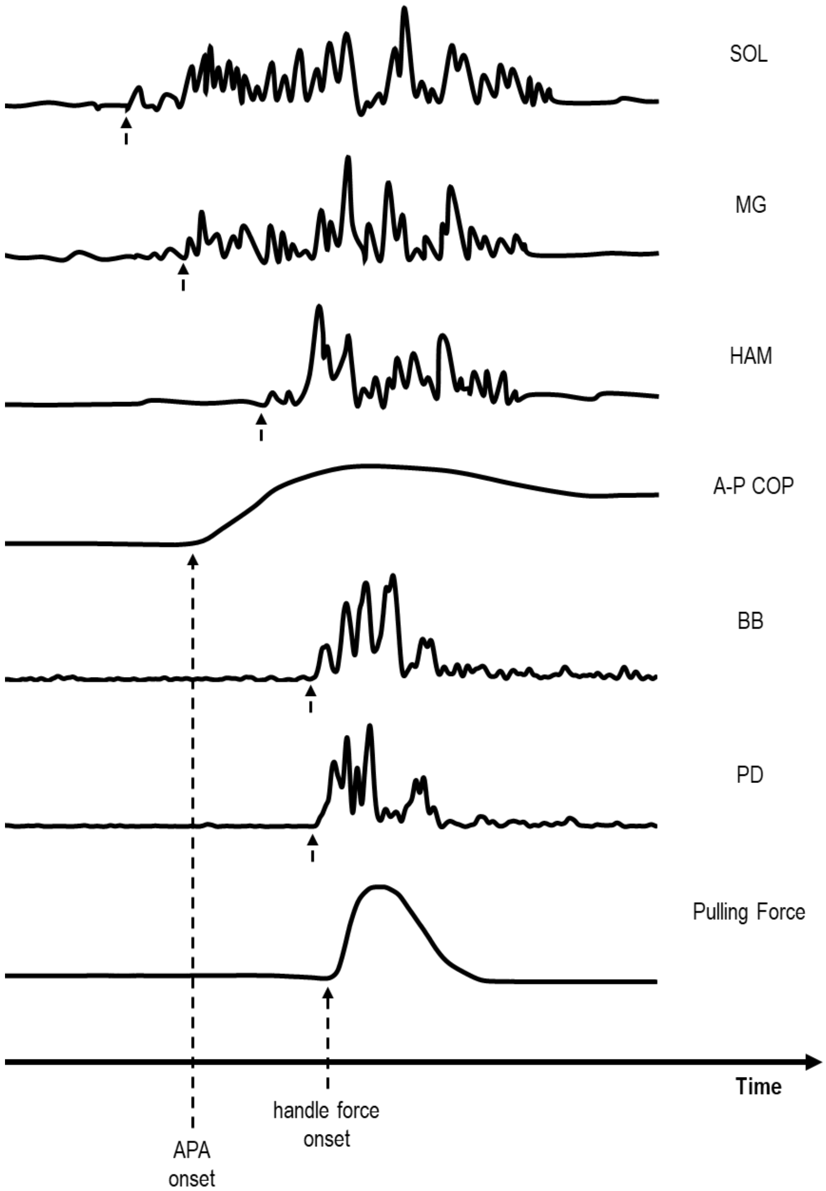


Figure 2. The typical sequence of events during a handle pull movement as adapted from Dietz et al. (2000). The presented EMG, COP, and pulling activity are from a single handle pull trial completed by a participant in the current study. The onset of the filtered and rectified EMG activity are labelled by the small arrows. Following the onset of postural muscle activation and APA onset, are the onsets of BB and PD EMG activity, and pulling force onset (Adapted from Dietz et al., 2000).

1.2.2 Scaling of APA magnitude

When pushing or pulling harder onto a handle, there will be a larger reaction force exerted from the handle to the body and consequently, a potentially greater disturbance to balance. Having a larger APA would allow the COM to start farther away from the BOS boundary, such that it would prevent the larger COM displacements with more forceful movements from causing a loss of balance. Fortunately, the postural control system is often able to adjust or scale the size of the APA to the size of the predicted disturbance to balance (Dietz et al., 2000; Elble & Leffler, 2000; Lee et al., 2015; Massion, 1992; Mochizuki, Ivanova & Garland, 2004; Weeks, 1994).

The importance of scaling the APA to the amount of force exerted was demonstrated by Lee et al. (1990), who had participants complete handle pulls from 10 to 95% of maximal pulling force (Fmax). Pulling force was positively correlated with APA magnitude, such that as the peak force generated from pulling increased, anticipatory EMG activity of the medial gastrocnemius (MG), HAM, and TA were increased. Normalized MG EMG activity increased by 205% as pulling force increased from 10% to 80% Fmax (Lee et al., 1990).

The peak ankle torque that results from the anticipatory muscle activity also increases with pulling force. The increase in anticipatory ankle torque with pulling force protectively propels the COM away from the handle and the BOS limits (Bleuse et al. 2006; Elble & Leffler, 2000; Weeks, 1994). Anticipatory ankle torque significantly increased from ~15 Nm to ~45 Nm from 10% to 40% Fmax (Lee et al., 1990). Although anticipatory ankle torque continued to increase to ~50 Nm by 80% Fmax, the increase was not statistically significant. This may have been as a result of the recruitment of the TA muscle observed at greater pulling force in some participants. Activation of the TA opposes the torque generated by the ankle from the MG activity.

1.2.3 Scaling of APA timing

In addition to APA magnitude scaling with increasing force, there is a modulation in the timing of the APA. Having an earlier APA or larger APA duration will allow the COM to start further away from the BOS boundary and preserve balance during more forceful pushing or pulling (Dietz et al., 2000; Elble & Leffler, 2000; Lee et al., 2015; Massion, 1992; Weeks, 1994). In the study conducted by Lee et al. (1990), as pulling force increased from 10% to 80% Fmax, APA onset, quantified as the start of MG EMG activity increased from -250 ms to -780 ms prior to pulling onset.

Weeks (1994) also observed a relationship between APA timing and the amount of force exerted during a handle pull task. For this study, participants completed isometric handle pulls ranging between 50% and 100% Fmax. APA onset was determined as the start of HAM EMG activity and referenced relative to the onset of the prime mover (i.e., PD) EMG activity (Weeks, 1994). Pulling force and APA onset data for each subject were standardized to a Z-scale. Weeks (1994) completed regression analyses between APA onset and pulling force to determine the scaling of APA timing to the amount of force exerted onto the handle. The slope of the regression lines for the right and left HAM were 0.678 and 0.695, respectively, in healthy young adults (Weeks, 1994). Thus, healthy young adults demonstrated earlier APA onsets with increasing pulling force and larger potential disturbances to balance (Lee et al., 2015; Massion, 1992; Weeks, 1994).

1.2.4 Detriments to the Scaling of APAs

Not all individuals are able to appropriately scale their APA magnitude or timing to the upcoming postural disturbance. In fact, an impaired ability to generate larger and earlier APAs with more forceful movements is often demonstrated by individuals with physiological deficits due to aging or neurological diseases, such as older adults (Elble & Leffler, 2000; Kanekar & Aruin, 2014; Kubicki, Mourey & Bonnetblanc, 2015; Lee et al., 2015; Weeks, 1994) and stroke patients (Pereira et al., 2014; Ustinova, Goussev, Balasubramaniam & Levin, 2004).

When Błaszczyk, Lore & Hansen (1997) had older and young adults complete a pushing and pulling task at varying forces (from 2.5 N to 50 N), they found that individuals demonstrated a reduced modulation of APA magnitude (i.e., COP displacement) with aging. When pushing and pulling at 15 N of force, COP displacement was ~12.5% larger in older than young adults. However, at 50 N of force, COP displacement was ~13.6% smaller in older than young adults. Thus, older adults tended to “over-respond” in situations of minimal internal postural disturbance or amount of force exertion and “under-respond” when greater postural stabilization was required. Similarly, Ustinova et al. (2004) found that individuals with stroke-related hemiparesis did not adapt anticipatory COP displacements with more rapid, and thus destabilizing, arm swing movements. It has been suggested that the inability to appropriately scale the APA magnitude (i.e., under- or over-responding) to an upcoming postural disturbance increases an individual’s risk of falling during a pushing or pulling task (Lee et al., 2015; Weeks, 1994).

An impaired ability to initiate earlier APAs with more forceful movements has also been observed with aging (Weeks, 1994) and stroke (Pereira et al., 2014). Older adults demonstrate a smaller degree of scaling of APA timing with changes in force exerted during an isometric handle pull (Weeks 1994). When the slope of the regression line between APA onset and pulling force was determined, it was found that older adults demonstrated slopes of 0.467-0.529, while young adults demonstrated steeper slopes of 0.678-0.698. The lesser scaling of APA onsets was a result of older adults exhibiting more homogenous HAM EMG onset times across a range of force levels (Weeks, 1994). Further, when Pereira et al. (2014) had individuals with stroke complete arm raises of differing speeds, changes in the timing of the APAs were absent, as evidenced by unvarying onsets of trunk muscle activation.

A consequence of more homogenous APA timing are tendencies to respond too early (i.e., over-respond) to minimal disturbances to balance and to respond too late (i.e., under-respond) to situations of greater disturbance to balance. For example, when completing handle pulls at submaximal force (20 N), older adults initiated APAs 61% earlier than the young adults (Stelmach, Populin & Müller, 1990). This may be due to older adults perceiving minimal disturbances to balance as more destabilizing and requiring an earlier APA response (Stelmach et al., 1990). In contrast, with greater force exertion, older adults initiate APAs later than young adults (Bleuse et al., 2006; Rogers, Kukulka & Soderberg 1992). Bleuse et al. (2006) found that young and older adults initiated COP displacements on average -256 ms and -148 ms prior to arm raise onset, respectively. In addition, Rogers et al. (1992) found that young adults activated postural muscles ~ 91% earlier relative to shoulder muscle activation than older adults. Thus, at maximal exertions of speed, APA onsets occurred later in older compared to young adults. In fact, it is possible for older adults to generate an APA after instead of before activation of the prime mover (Woollacott & Manchester, 1993).

It is evident from these studies that a reduced ability to scale APA timing or magnitude has functional consequences to postural control. Specifically, an inappropriate scaling of APA can result in an insufficient amount of time to generate adequate amplitude of postural muscle activity to maximize the displacement of their COM from the BOS limits prior to initiation of the task (Massion, 1992; Weeks, 1994). Thus, it is important to delineate the factors that may be responsible for a reduced ability in APA scaling. One possible factor that is common to both older adults and individuals with stroke is an elevated emotional state (i.e., increasing feeling of anxiety or fear of falling) (Legters, 2002). This can be experimentally examined by incorporating a postural threat paradigm.

1.3 Postural Threat

1.3.1 Effect of Postural Threat on Postural Control

Previous research has implemented various postural threat paradigms to examine how individuals respond to a threat to their balance. Postural threat has been introduced in numerous forms but two of the more common methods are 1) increasing the height and minimizing the surround of the support surface and 2) subjecting participants to the possibility of an external disturbance to their balance (e.g., an external trunk perturbation or translation of the support surface) (Brown, Polych & Doan, 2006; Carpenter, Adkin, Brawley & Frank, 2006; Carpenter, Frank, Silcher & Peysar, 2001; Davis, Campbell, Adkin & Carpenter, 2009; Gendre et al., 2016; Huffman, Horslen, Carpenter & Adkin, 2009; Johnson, Zaback, Tokuno, Carpenter & Adkin, 2017; Phanthanourak et al., 2016; Shaw, Stefanyk, Frank, Jog & Adkin, 2012; Sturnieks, Delbaere, Brodie & Lord, 2016; Yiou et al., 2011; Zaback, Carpenter & Adkin, 2016; Zaback, Cleworth, Carpenter & Adkin, 2015). Standing at the edge of an elevated support surface height acts as a postural threat by increasing the consequences associated with experiencing a loss of balance (Brown et al., 2006). In contrast, subjecting participants to the possibility of a perturbation increases the likelihood for individuals to experience a fall (Phanthanourak et al., 2016).

Regardless of the threat paradigm, it has consistently been found that in the presence of a postural threat, individuals respond with an increased level of physiological arousal and emotional state (e.g., anxiety and fear of falling) (Adkin et al., 2002; Brown et al., 2006; Carpenter et al., 2006; Carpenter et al., 2001; Davis et al., 2009; Johnson et al., 2017; Phanthanourak et al., 2016; Zaback et al., 2015). Although physiological arousal, anxiety, and fear of falling are closely related, they are also distinct. Whereas physiological arousal refers to an individual’s autonomic responsiveness or alertness, it is nondirective (Hadjistavropoulos, Delbaere & Fitzgerald, 2011; Pijpers, Oudejans & Bakker, 2005). Being in a state of anxiety involves feelings of unease and apprehension in anticipation of an event or outcome, as well as physiological arousal or somatic anxiety (Brown et al., 2006; Hadjistavropoulos et al., 2011; Pijpers et al., 2005). Fear of falling is the ongoing worry about experiencing a fall, and is dependent on the individual’s confidence in their ability to avoid a fall (Hadjistavropoulos et al., 2011; Legters, 2002; Tinetti and Powell, 1993). As a result of these threat-induced increases in arousal, anxiety and fear, alterations in postural control during quiet standing are also observed (Brown et al., 2006; Carpenter et al., 2006; Carpenter et al., 2001; Davis et al., 2009; Huffman et al., 2009; Johnson et al., 2017; Shaw et al., 2012; Sturnieks et al., 2016; Zaback et al., 2016; Zaback et al., 2015). However, the specific consequences to postural control appear to be dependent on the individual and the level of threat.

When young adults stand on an elevated surface up to 1.6 m above ground, they adopt a stiffer postural control during standing. This is reflected by smaller COM displacements, as well as smaller and more frequent displacements of the A-P COP (Brown et al., 2006; Carpenter et al., 2006; Carpenter et al., 2001). There is also an increase in TA and rectus femoris EMG activity, as well as a decrease in SOL and MG EMG activity, resulting in a posterior shift of the body's COM position (Brown et al., 2006; Carpenter et al., 2006; Carpenter et al., 2001; Huffman et al., 2009; Zaback et al., 2015). Since these individuals are standing with the edge of the elevated surface directly in front, it is believed that moving the COM away from the edge is a strategy to reduce the probability of experiencing a loss of balance (Brown et al., 2006).

While surface heights of up to 1.6 m have been successful in eliciting a threat-related response in healthy young and older adults, the observed responses are often different to those exhibited by older adults with a fear of falling (Davis et al., 2009; Maki, Holliday & Topper, 1991). Rather, it is necessary to present a stronger postural threat by having healthy young adults stand at the edge of a surface that is 3.2 m high. In this situation, those who report being fearful demonstrate larger and more frequent COM displacements, which is a postural control strategy often demonstrated by fearful older adults (Davis et al., 2009; Maki et al., 1991). In contrast, young adults who did not report being fearful continued to demonstrate a stiffening strategy when standing at 3.2 m (Davis et al., 2009).

Similar to the elevated surface height paradigm, the anticipation of an external perturbation, such as a push to the trunk (Shaw et al., 2012) or a support surface translation (Johnson et al., 2017), can elicit elevated feelings of anxiety in healthy young adults. Further, healthy young adults demonstrate more frequent and larger trunk movements (Shaw et al.,

2012) and COP displacements (Johnson et al., 2017) during standing when expecting an external perturbation. Since a similar control of posture is observed in fearful older adults when standing (Maki et al., 1991), this may suggest that evoking a postural threat response in healthy young adults via the risk of an external disturbance to balance causes young adults to control posture similarly to fearful older adults.

1.3.2 Effects of Postural Threat on APAs

Postural threat, and the resulting changes in arousal, anxiety and fear of falling, is also known to influence anticipatory postural control. However, the observed effects of postural threat on APAs are not as consistent as the effects of postural threat during quiet standing. The differences found in the literature suggest that the effects of postural threat may depend on the movement task, the type and the perceived proximity of the threat, as well as the congruency between the threat and the direction of the task (Gendre et al., 2016; Phanthanourak et al., 2016).

Healthy young adults initiate earlier APAs during a rapid leg raise when postural threat is presented in the form of an elevated surface than under non-threatening conditions (Gendre et al., 2016; Yiou et al., 2011). However, during a rise to toes task completed at elevated (i.e., threatening condition) and low (i.e., non-threatening condition) surface heights, healthy young adults do not alter APA duration (Adkin et al., 2002). This was evidenced by no differences in the time from the onset of COP displacement to when peak backwards COP displacement was achieved between threatening and non-threatening conditions (Adkin et al., 2002). It should be noted, that healthy young adults did demonstrate later anticipatory muscle activation (i.e., less time between TA onset and peak backwards COP displacement) with postural threat (Adkin et al., 2002). However, this did not result in a functional change based on the similar COP APA timing between conditions.

When postural threat is induced by increasing surface height, APAs also tend to be slower and smaller in size, where the amount of decrease depends on the perceived proximity of the threat. For example, Gendre et al. (2016) had healthy young adults complete lateral leg raises with either the foot of their stance or swing leg at the edge of an elevated (1.0 m) surface. When the foot of the stance leg was located at the surface edge, the leg raise caused the participant’s COM to approach the surface edge and thus, increase the proximity of the postural threat (Gendre et al., 2016). In contrast, when the foot of the swing leg was positioned at the surface edge, the leg raise resulted in the body’s COM to move away from the surface edge and consequently, reduce the proximity of the postural threat. Gendre et al. (2016) found that when lateral leg raises were completed so that the COM would approach (i.e., increase proximity) rather than avoid (i.e., decrease proximity) the elevated surface edge, participants demonstrated a greater decrease in APA magnitude. This strategy reduces the likelihood of experiencing a fall at the edge of an elevated surface because minimizing APA magnitude when approaching the threat maximizes the distance between the body’s COM and the edge of the elevated surface (Adkin et al., 2002; Brown et al., 2006; Carpenter et al., 2001). Similar to the healthy young adults under postural threat, when pushing or pulling at maximal force under non-threatening conditions, older adults also demonstrate smaller APA magnitudes when compared to young adults (Lee et al., 2015). This may suggest that the “under-response” of APAs that older adults exhibit when greater postural stabilization is required may partially be due to increased feelings of anxiety and fear of falling among older adults.

When postural threat is presented in the form of a potential M-L surface translation, the timing of APAs during a rise to toes task is largely unaffected (Phanthanourak et al., 2016). However, rather than APA magnitude becoming smaller, as observed when performing a movement at height (Adkin et al., 2002; Gendre et al., 2016; Yiou et al., 2011;Zaback et al., 2016; Zaback et al., 2015), APA magnitude becomes larger with the potential of experiencing an external perturbation (Phanthanourak et al., 2016). This altered strategy is similar to when older adults demonstrated oversized APA magnitudes when pushing or pulling at submaximal forces under non-threatening conditions (Błaszczyk et al., 1997). This suggests that the tendency to "over-respond" in situations of minimal internal postural disturbance observed with aging may partially be due to elevated feelings of anxiety and fear of falling in older adults. Phanthanourak et al. (2016) observed a 35% increase in TA EMG activity and a 19% increase in peak backward COP displacement in healthy young adults during a rise to toes task when the threat was present compared to when the threat was absent (i.e., performing the same movement on an unmoving surface). The difference in the changes in APA magnitude from previous studies could simply be attributed to the form of postural threat being dissimilar (i.e., potential perturbation versus elevated surface height). However, Phanthanourak et al. (2016) suggested that the relationship between the direction of the threat (M-L) and the direction of the APA (A-P) might also influence the effect of postural threat on anticipatory postural control.

As demonstrated by Gendre et al. (2016), the proximity of the threat can further decrease APA magnitude. However, when the APA direction and threat direction are independent of each other, strategically executing smaller APAs would only compromise performance on the rise to toes task (Adkin et al., 2002) and not reduce the proximity to the threat. Thus, this strategy may not have been employed when postural threat was presented in the form of a potential M-L perturbation. This is evidenced by participants not compromising movement execution, and in fact demonstrating better performance by rising more quickly onto the toes with postural threat (Phanthanourak et al., 2016). Individuals have previously been shown to increase performance on a given task with increased arousal, independent of valence (Schmidt, Cléry-Melin, Lafargue, Valabrègue, Fossati, Dubois & Pessiglione, 2009). Thus, the larger APA magnitudes with threat observed by Phanthanourak et al. (2016) may have occurred due to participants executing larger movements with elevated physiological arousal (Schmidt et al., 2009).

Performance on rapid leg raise and rise to toes tasks rely on APAs to destabilize the COM and initiate movement. It is evident from these previous studies that postural threat influences the generation of these APAs (Adkin et al., 2002; Gendre et al., 2016; Phanthanourak et al., 2016; Yiou et al., 2011; Zaback et al., 2016; Zaback et al., 2015). APAs meant to predictively stabilize the COM that accompany arm raise, pushing and pulling tasks and whether they are influenced by a threat-related response (i.e., elevated physiological arousal, anxiety, fear of falling) have yet to be examined. Additionally, one limitation of previous studies examining APAs is that the required movements have always been performed at a single intensity, such as completing the movement at maximal speed or exertion. Since no studies have introduced postural threat across a range of movement intensities for a given task, it is unknown whether postural threat also influences an individual's ability to scale APA magnitude and timing to the amount of destabilization associated with the movement task.

2.0 Rationale, Purpose, Research Question, and Hypothesis

2.1 Rationale

The completion of everyday tasks, such as attempting to pull open a heavy door or drawer, result in forces that act to destabilize the body (Massion, 1992; Pollock et al., 2000). Unfortunately, older adults and individuals with neurological diseases, such as stroke, are more susceptible to falls when completing everyday tasks, as they demonstrate a reduced ability to generate postural adjustments appropriate in size and timing in anticipation of the destabilizing task (Błaszczyk et al., 1997; Lee et al., 2015; Pereira et al., 2014; Rogers et al., 1992; Stelmach et al., 1990; Ustinova et al., 2004; Weeks, 1994).

Changes in the generation of APAs are often attributed to the physiological declines that accompany the aging or neurological disease process (Pereira et al., 2014; Sturnieks et al., 2008; Takacs et al., 2013). However, psychological factors, such as elevated feelings of anxiety and fear in response to a threat to posture have also been shown to alter anticipatory postural control (Adkin et al., 2002; Gendre et al., 2016; Phanthanourak et al., 2016; Yiou et al., 2011). It is currently unknown how postural threat influences the ability to adapt the size and timing of APAs to match the demands of the task. This is important to examine because inappropriately sized or timed APAs may impede individuals from effectively maintaining balance and avoiding falling when completing the task (Lee et al., 2015; Massion, 1992; Weeks, 1994). If elevated anxiety and fear of falling impair the generation of APAs even in the absence of the physiological deficits with aging and disease (i.e., in healthy young adults), reducing feelings of anxiety and fear in populations at increased fall risk may be an effective means of improving the generation of appropriately sized and timed APAs and thus prevent falls.

2.2 Purpose

The purpose of this thesis is to investigate whether a threat-related response elicited by M-L surface translations influences the scaling of APA magnitude and timing to the amount of force exerted during a handle pull task in healthy young adults.

2.3 Hypothesis

It is hypothesized that young adults will demonstrate a reduced scaling of APA magnitudes and timing when in the presence of postural threat. This will be reflected by more homogenous APA amplitudes and onsets across a range of pulling forces (Błaszczyk et al., 1997; Rogers et al., 1992; Stelmach et al., 1990; Weeks, 1994; Woollacott & Manchester, 1993).

3.0 Methods

3.1 Participants

Nineteen healthy young adults (7 F, 12 M, mean ± 1 SD age of 24 ± 2 y, mass of 69.6 ± 9.9 kg, height of 1.70 ± 0.10 m) gave written informed consent to participate in this study. All participants reported no known neuromuscular (e.g., recent sprain or strain, Parkinson's disease, etc.) or orthopedic (e.g., recent fracture, osteoporosis, osteoarthritis, etc.) disorders or injuries that could affect their balance. In addition, individuals with hearing difficulties or disorders were not eligible to participate in the study due to the experimental protocol.

3.2 Experimental Setup

Participants arrived to the laboratory wearing a sleeveless shirt and shorts that did not go past the participant's knees. Upon arrival, participants were equipped with a body harness that was later attached to a low-friction overhead track. The purpose of the harness was to prevent the participant from falling in the event that they were unable to recover their balance during the experimental trials.

Skin conductance was obtained using an electrodermal activity (EDA) unit (EDA100C, BIOPAC Systems Inc., Goleta, CA, USA). Skin conductance was collected from the participant's non-dominant hand, as they were required to complete questionnaires periodically throughout the study. Prior to placement of the reusable electrodes (TSD203, BIOPAC Systems Inc., Goleta, CA, USA), the front of the index and middle fingers at the distal phalanges were cleansed with alcohol. An isotonic electrode gel (GEL101, BIOPAC Systems Inc., Goleta, CA, USA) was then applied to the cleansed skin areas, as well as the 1.66 mm diameter gel cavity of the paired electrodes. The electrodes were then secured to the prepared skin areas by its Velcro strap components. The Velcro straps were taped to the hand to further prevent displacement of the electrodes.

Surface EMG recordings were obtained from the BB and PD muscles of the right arm, and the SOL, MG and HAM of the right leg. EMG data was only collected from the one side as it was assumed that muscle responses between the left and right sides of the body would be symmetrical (Adkin et al., 2002). Prior to electrode placement, the skin sites of the muscles of interest, as well as the outside of the right knee, were shaved, cleansed with alcohol, and lightly abraded with a conductive gel (NuPrep, Weaver and Company, Aurora, CO, USA) to minimize skin impedance. Pairs of surface electrodes (32 mm diameter, 5 mm interelectrode distance, Kendall Meditrace 200, Mansfield, MA, USA) were positioned over the BB, PD, SOL, MG, and HAM, with electrode placements based on guidelines by Cram & Kasman (2010). A single reference electrode (32 mm diameter, Kendall Meditrace 200, Mansfield, MA, USA) was placed on the lateral aspect of the right knee.

3.3 Experimental Protocol

Participants stood barefoot and with their feet shoulder width apart on a forceplate (0.46 m x 0.51 m, AMTI, OR6-7-2000, Watertown, MA, USA) that was flush with a 1.83 m x 0.92 m wooden platform fixed to a motorized 4.3 m translation stage (H2W Technologies Inc., Valencia, CA, USA) (Figure 3). Throughout the experiment, a spotter was positioned beside the platform, and the participant’s harness was attached to an overhead track to prevent the participant from experiencing a fall.

The handle pull device consisted of a 0.7 m long horizontal steel handle bar that was attached to a strain gauge transducer by a 0.85 m long metal wire and a steel frame (Figure

3). Since the metal wire was able to yield to movement in the M-L direction, participants were prevented from utilizing the handle pull device to stabilize the body in case of a loss of balance. For each participant, the handle and strain gauge transducer were adjusted in height so that the connecting wire, as well as the participant's forearms were parallel to the ground when the participant's elbows were flexed at ~90 degrees. Throughout the experiment, participants were positioned so that they gripped the bar with their hands placed shoulder width apart and their elbow's flexed at ~90 degrees. From this initial position, participants completed the handle pull task.

Each handle pull trial commenced with the researcher verbally outlining the amount of force the participant should aim to exert during the upcoming pull. Participants were then presented with an auditory "warning" tone that prompted the participant of an upcoming "go" tone. One to four seconds following the "warning" tone, participants were presented with a higher pitched "go" tone. As soon as participants heard the "go" tone they were to pull onto the handle with the instructed amount of force. For the pull, participants were to rapidly achieve the goal force and then immediately release from the pull rather than maintaining the peak force for a prolonged duration (Figure 2).

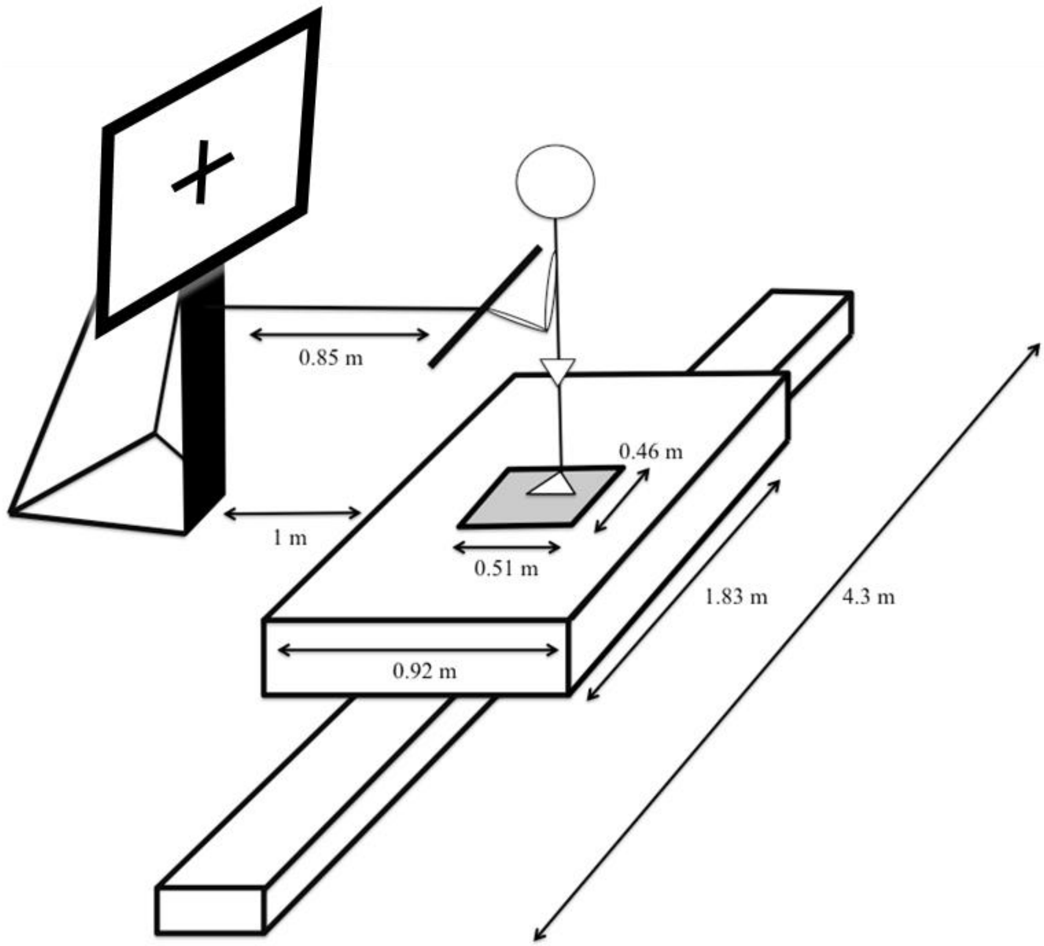


Figure 3. A diagram of the proposed experimental setup depicting a participant standing on a forceplate flush with a wooden platform. The platform, which was attached to a motor-driven linear positioning stage (H2W Technologies Inc., Valencia, CA, USA), was capable of delivering surface translations in the M-L direction. Participants were required to pull on a steel handle attached to a stand anchored to the ground 1 m from the platform.

Prior to the experimental conditions, participants completed a minimum of five handle pulls when cued by the “warning” and “go” tones. The handle pulls were completed at the participant’s preferred amount of force exertion and were meant to familiarize the participants to the handle pull task and the auditory cues. Once familiarized to the task, participants completed handle pulls at maximal force exertion. At the “go” tone, participants were to pull as hard as they could on the handle using their BB muscle without allowing the heels of their feet to leave the forceplate. The participant's maximum pulling force (Fmax) was determined as the greatest peak force achieved during the largest of three maximal pulls.

Following the determination of the participant's Fmax, participants completed a practice block consisting of 12 handle pull trials occurring 10-15 s apart. Participants were aware that the handle pull trials would be completed with the platform remained locked in place (i.e., No Threat). The purpose of these practice trials was to reduce the potential for a learning effect during the experimental conditions. For the duration of the practice block, real-time feedback was provided on a monitor located 1 m in front of the participant and consisted of the participant's actual pulling force relative to a static line depicting their Fmax. For the first and last trials, identical to the maximal pulling trials, participants were instructed to pull as hard as they could on the handle without lifting their heels at the auditory "go" tone. For the remaining ten handle pull trials, the instructions were randomized in order, where participants were told to attempt to pull at either 50%, 60%, 70%, 80%, or 90% of their Fmax at the "go" tone. The purpose of the instructions was to ensure that participants were completing pulls at varying forces. Participants were informed that inaccurate handle pulls would not be discarded to minimize any feelings of anxiety that participants may have towards accurately reaching the goal force.

Following the practice trials, participants completed two experimental conditions, a No Threat and Threat condition. During the experimental conditions, participants were not given visual feedback of their pulling performance and were instead instructed to keep their eyes focused on a target presented on the monitor (Figure 3). The removal of feedback was meant to minimize the amount of over-correcting to achieve the stated goal force. In addition, similar to the practice condition, participants were instructed that inaccurate handle pulls would not be discarded. Participants completed all of the No Threat handle pull trials prior to the Threat condition trials. The threat was introduced following the No Threat condition to prevent prior experience with postural threat to influence the control of posture even in the absence of the threat (Adkin, Frank, Carpenter & Peysar, 2000).

During the No Threat experimental condition, participants completed 36 handle pull trials that occurred 10-15 s apart. Participants were given a mandatory two-minute seated rest period after every block of 12 trials to prevent fatigue. Participants were informed that the platform that they were standing on would remain unmoving and locked in place for the entirety of the condition. Identical to the practice block, each No Threat block commenced and ended with a maximal pulling trial. The instructions given for the remaining handle pull trials were randomized in order, and the given "goal forces" ranged from 50% to 90% of Fmax.

Following the No Threat experimental condition, participants then completed the Threat experimental condition. Participants were informed that the platform that they were standing on may or may not move in the leftward or rightward direction at any time following the "warning" tone. Thus, participants were aware that they could experience a surface translation in the M-L direction (0.25 m displacement, 0.7 m/s peak velocity, 1.6 m/s^2 peak acceleration) prior to the "go" tone, simultaneous with the "go" tone, or any time following the "go" tone, or that the surface would not move. Exposing individuals to surface translations in the M-L direction has previously been shown to elicit a threat-related response (i.e., elevated physiological arousal, perceived anxiety and fear of falling) in healthy young adults (Phanthanourak et al., 2016). The anticipation of experiencing a surface translation in the M-L direction with or following the "go" tone ensured participants would feel threatened throughout the duration of the handle pull task.

The Threat condition consisted of 45 handle pull trials occurring 10-15 s apart. Participants were given a mandatory two-minute rest period after every 15 trials. Similar to the practice and No Threat conditions, each trial commenced with the pulling force instructions followed by an auditory "warning" tone. For the first and last trial of each block participants were instructed to pull as hard as they could without lifting their heels, and for the remaining trials participants were randomly instructed to pull between 50% and 90% of Fmax. On five of 15 trials, the platform remained stationary and the "warning" tone was followed by the "go" tone, cuing participants to complete the handle pull at the instructed force. On seven of 15 trials, the platform translation occurred 0.8-3 s after the "go" tone, and followed handle pull completion. The translation also occurred at the "go" tone for two trials and before the "go" tone for one trial. During these three trials, participants were unable to perform the handle pull in completion. In response to the platform translation, participants were instructed to recover their balance however they deemed necessary. Pulling force instructions and platform translation settings were pseudo-randomized to ensure a sufficient amount of handle pull trials could be allocated to each goal force. Participants were blind to the order of the experimental trials.

3.4 Data Collection and Analyses

3.4.1 Physiological Arousal and Psycho-social Measures

Measures of physiological arousal, perceived anxiety and perceived fear were obtained to quantify the postural threat response (Adkin et al., 2002; Phanthanourak et al., 2016). An increase in arousal, anxiety, and fear would confirm that the surface translation was successful in eliciting postural threat in the healthy young adults.

Physiological arousal was estimated by measuring changes in skin conductance (electrodermal, EDA) activity of the palm. The EDA signal was recorded using a data acquisition software (Spike2, Cambridge Electronics Design, Cambridge, UK) at a sampling frequency of 1000 Hz (micro1401, Cambridge Electronics Design, Cambridge, UK). The raw signal was filtered offline using a second-order Butterworth low-pass (10 Hz) filter (Adkin et al., 2002; Stegeman & Hermens, 2007). For each handle pull trial, the average EDA during the 2 s immediately prior to the “go” tone was calculated (Phanthanourak et al., 2016). Ensemble averages were calculated for each condition.

Although closely related, perceived anxiety related to posture and fear of falling are separate constructs and were measured independently (Davis et al., 2009; Hadjistavropoulos et al., 2011). Prior to each experimental condition, participants were asked to rate their confidence in their ability to maintain their balance and avoid a fall during the handle pull trials of that block on a scale of 0% (not at all confident) to 100% (completely confident) (Adkin et al., 2002; Davis et al., 2009; Phanthanourak et al., 2016) (Appendix I). Perceived confidence was collected as it is associated with a fear of falling (Hadjistavropoulos et al., 2011; Legters, 2002; Tinetti and Powell, 1993). At the end of each experimental condition, participants were asked to rate how fearful of falling they felt when completing the handle pulls on a scale of 0-100% (0% = no fear, 100% = extremely fearful) to assess perceived fear of falling (Adkin et al., 2002; Davis et al., 2009; Phanthanourak et al., 2016) (Appendix I). In addition, participants completed a 16-item state anxiety survey modified from Smith, Smoll & Schutz (1990). Each item was scored on a scale of 1-9 (1 = “I did not feel this at all”, 9 =

"I felt this extremely"), and the 16 scores were summed (Davis et al., 2009; Carpenter et al., 2006) (Appendix II).

3.4.2 Pulling Force

A strain gauge transducer attached to the handle device recorded the pulling force exerted onto the handle at a sampling rate of 1000 Hz (micro1401, Cambridge Electronics Design, Cambridge, UK). For each handle pull trial, baseline force was defined as the average force activity that occurred during the 200 ms interval following the "warning" tone. Next, pulling force onset was defined to occur when the force signal was 2 SDs above baseline. An algorithm was written in Spike2 (Spike2, Cambridge Electronics Design, Cambridge, UK) to determine pulling onset for each trial and each onset was later confirmed by visual inspection. Peak force and peak rate of force exertion were also obtained from the force signal. Finally, time to peak force was calculated as the interval from pulling force onset to peak force for each handle pull trial.

3.4.3 Surface EMG

EMG activity from the BB, PD, SOL, MG, and HAM were amplified 350 times (MA-300, Motion Systems Inc., Baton Rouge, LA, USA) and recorded using a data acquisition program (Spike2, Cambridge Electronics Design, Cambridge, UK) at a sampling rate of 1000 Hz (micro1401, Cambridge Electronics Design, Cambridge, UK). For each handle pull trial, the EMG onset for each muscle was determined visually by the researcher from the rectified and unfiltered EMG signal. The EMG onsets were determined as the point when the EMG activity first appeared to be larger than baseline EMG activity for at least 50 ms, where baseline EMG activity was considered to occur during the 250 ms interval following the "warning" tone (Adkin et al., 2002; Phanthanourak et al., 2016).

For each handle pull trial, EMG amplitude for all muscles were quantified by the root mean square (RMS) over the 250 ms interval following EMG onset of the respective muscle (Adkin et al., 2002). EMG amplitudes were calculated from the rectified and filtered (fourth order, low-pass Butterworth filter set at 50 Hz) EMG signals. Although instructed to complete the pulls using only their BB muscles, participants also tended to activate their PD muscle when executing the handle pulls. Thus, EMG amplitude of the BB and PD quantified the amount of potential internal disturbance to balance during the pull.

3.4.4 Centre of Pressure

COP was calculated from the force and moment signals obtained from the forceplate (AMTI, OR6-7-2000, Watertown, MA, USA) on which the participants stood. The forceplate signals were sampled at a rate of 1000 Hz (micro1401, Cambridge Electronics Design, Cambridge, UK) and recorded using a data acquisition software (Spike2, Cambridge Electronics Design, Cambridge, UK). COP analyses were limited to the A-P direction for this study, as the pulling movement and the associated APA occur in the A-P direction (Elble & Leffler, 2000; Weeks, 1994).

For each handle pull trial, COP displacement at pulling onset was determined as the difference in COP position from the onset of forward COP movement (i.e., COP onset) to pulling force onset. The COP onset for each handle pull trial was defined as the point at which the COP trace moved 2 SDs above quiet standing COP activity (i.e., baseline). Baseline COP for each trial was the mean COP activity during the 200 ms interval following the “warning” tone (Phanthanourak et al., 2016). An algorithm was written in Spike2 (Spike2, Cambridge Electronics Design, Cambridge, UK) to determine the onset of forward COP movement, and each onset was later confirmed by visual inspection. Peak forward COP displacement velocity for each handle pull trial was represented by the largest slope value attained from the COP position signal following COP onset. Peak forward COP velocity was determined by an algorithm that was written in Spike 2 (Spike 2, Cambridge Electronics Design, Cambridge, UK), and later confirmed by visual inspection.

3.5 Statistical Analysis

The effect of postural threat on physiological arousal and psycho-social factors were determined by performing paired sample Student *t*-tests on the average EDA activity, and perceived confidence, anxiety, and fear of falling questionnaire results from the No Threat and Threat conditions.

Differences in maximal force exertion or movement execution as a result of postural threat were analyzed by performing paired sample Student *t*-tests on BB and PD EMG amplitude, and peak force exertion, peak rate of force exertion, and time to peak force exertion during maximal pulling trials between the No Threat and Threat conditions. Paired sample Student *t*-tests were also performed on APA magnitude and onset measures during maximal pulling trials between conditions to determine the influence of postural threat on APAs to stabilize the body.

APA magnitude for each handle pull trial was quantified by the SOL, MG, and HAM EMG amplitudes, as well as COP displacement at pulling force onset and peak forward COP displacement velocity. For each participant, the scaling of APA magnitude for each condition was represented by the calculated slopes of the regression lines between the APA magnitude measures and the peak pulling forces for that condition.

APA onset for each handle pull trial was represented by the EMG onsets of the SOL, MG, and HAM muscles, as well as COP onset, and were reported relative to the pulling force onset. The scaling of APA timing was reflected by the slope of the regression lines between the APA onset measures and the peak pulling forces for each condition.

For each slope, the strength of the relationship and the amount of shared variability between the dependent measure and the pulling force were represented by standardized regression coefficients or Pearson's correlation coefficient, r, and the coefficient of determination, R^2, respectively.

The effect of postural threat on the scaling of APA magnitude and APA timing to force exertion was analyzed by performing paired sample Student *t*-tests between the calculated slope, r and R^2 values of the No Threat and Threat conditions.

All statistical analyses were performed using Statistical Packages for the Social Sciences version 22 (IBM SPSS Statistics 22, Chicago, IL, USA). Data for each dependent measure were first checked for normality using Shapiro-Wilk tests of normality (Ghasemi & Zahediasl, 2012). If normality was violated, then the Wilcoxon signed-rank test was performed instead of the paired sample Student *t*-test. Significance for all tests was set to $p \leq 0.05$. When a test was found to be significant, effect size was calculated using Cohen's *d* for normally distributed data (Dunlap, Cortina, Vaslow & Burke, 1996) and the effect size estimate, *r*, for non-normally distributed data (Field, 2013; Rosenthal, 1991, p.19, [2.18]). All data are presented in the Results section as the mean ± one standard error of the mean.

4.0 Results

4.1 Physiological Arousal and Psycho-Social Measures

Participants had 14% greater EDA during the Threat (5.88 ± 0.34 μS) compared to the No Threat (5.18 ± 0.38 μS) condition (T = 157, p = 0.013, r = 0.57). In addition, participants reported being 34% less confident in their balance (T = 0.00, p < 0.001, r = -0.81), 46% more fear of falling (T = 190, p < 0.001, r = 0.88), and 29% more anxious during the Threat compared to the No Threat condition (T = 190, p < 0.001, r = 0.88) (Figure 4).

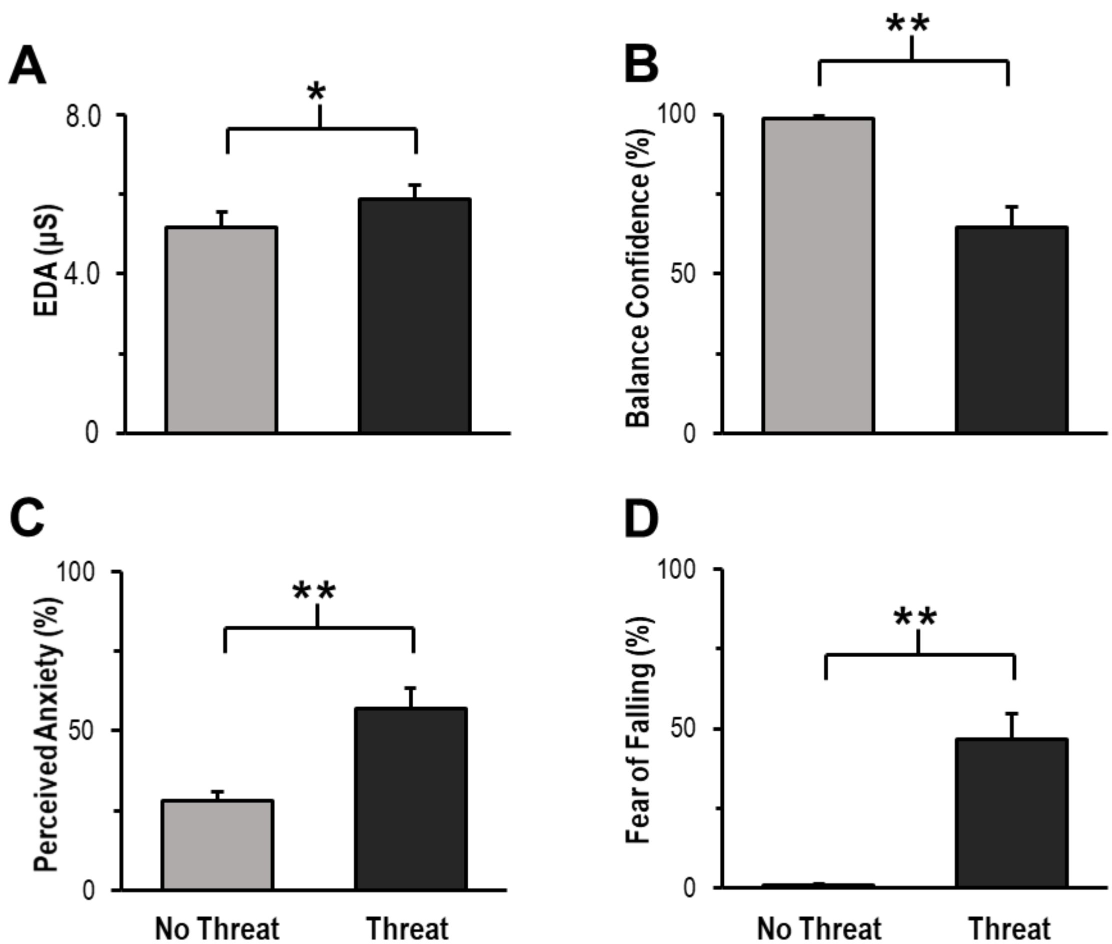


Figure 4. Mean ± 1 SE (A) skin conductance activity, (B) balance confidence, (C) anxiety, and (D) fear of falling during the No Threat and Threat conditions.
* = p < 0.05, ** = p < 0.001.

4.2 APAs During Maximal Force Exertion

Participants exerted a 5.8% larger force during the Threat (389.33 ± 32.31 N) compared to the No Threat (367.96 ± 32.18 N) condition when instructed to pull as hard as possible ($t(18) = -2.337$, $p = 0.031$, $d = 0.15$) (Figure 5). In addition, participants took 35% longer to reach peak force during the maximal pull trials of the Threat (179.25 ± 41.97 ms) compared to No Threat (132.40 ± 8.06 ms) condition ($T = 145$, $p = 0.044$, $r = 0.46$). The peak rate of force exertion during the No Threat and Threat conditions were 4.33 ± 0.49 N/ms and 4.53 ± 0.49 N/ms, respectively, and were not different between conditions ($t(18) = -1.195$, $p = 0.248$). Similarly, none of the EMG amplitudes were different between conditions. For example, the BB EMG amplitude during the No Threat and Threat conditions were 0.164 ± 0.030 mV and 0.143 ± 0.023 mV, respectively ($T = 33.0$, $p = 0.220$). As well, mean PD EMG amplitude was 0.257 ± 0.031 mV and 0.294 ± 0.038 mV during the the No Threat and Threat conditions, respectively ($t(18) = -1.177$, $p = 0.255$).

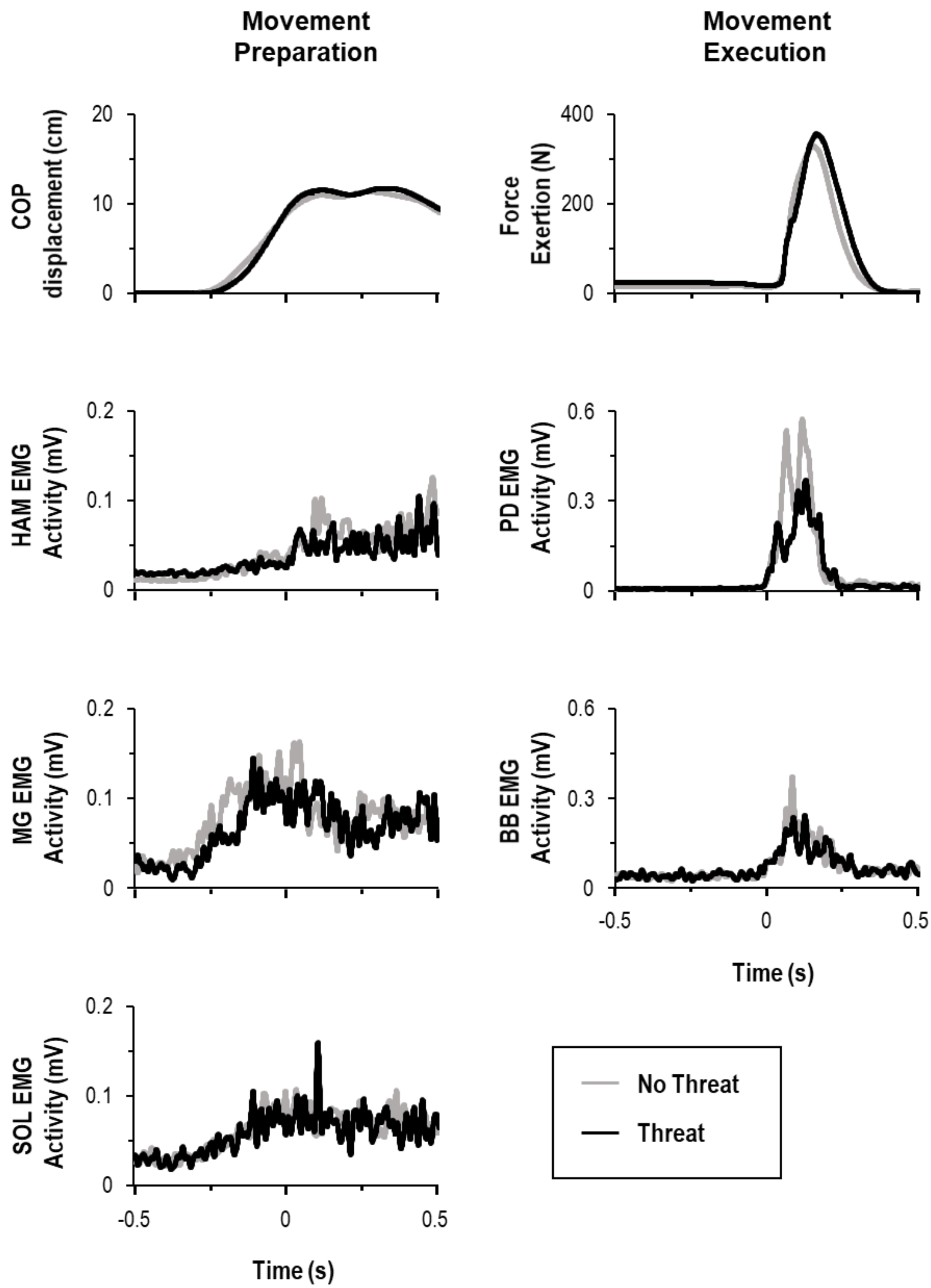


Figure 5. Point-by-point averaged movement preparation (APA) and movement execution traces obtained from all maximal pulling trials for a single participant.
Time @ 0 s = pulling onset.

Although participants exerted greater maximal force with postural threat, the APA generally did not change with threat. Specifically, HAM EMG activity was smaller during maximal pulls with postural threat ($T = 0.00$, $p = 0.020$, $r = -0.54$) but there were no differences in MG ($T = 37.5$, $p = 0.573$) and SOL ($T = 21.5$, $p = 0.608$) EMG activity (Table 1 and Figure 5). The resulting COP displacement ($t(18) = 0.381$, $p = 0.708$) and peak COP velocity ($t(18) = -1.276$, $p = 0.218$) were also not different between conditions (Table 1). In addition, although MG EMG onsets occurred 12.1% later with postural threat ($T = 150$, $p = 0.027$, $r = 0.51$), there were no differences in the SOL ($T = 143$, $p = 0.053$) and HAM ($T = 120$, $p = 0.314$) EMG onsets, and COP onsets ($t(18) = -0.749$, $p = 0.464$) between the No Threat and Threat conditions (Table 1).

	No Threat	**Threat**
APA magnitude		
MG amplitude (mV)	0.113 ± 0.036	0.096 ± 0.029
SOL amplitude (mV)	0.043 ± 0.003	0.044 ± 0.003
HAM amplitude (mV) *	**0.051 ± 0.025**	**0.023 ± 0.003**
COP displacement (cm)	5.04 ± 0.67	4.95 ± 0.69
COP velocity (cm/s)	51.20 ± 2.53	53.83 ± 2.90
APA timing		
MG EMG onset (ms) *	**-207.14 ± 21.20**	**-182.02 ± 15.71**
SOL EMG onset (ms)	-186.03 ± 20.77	-164.94 ± 14.78
HAM EMG onset (ms)	-118.38 ± 15.51	-107.03 ± 13.83
COP onset (ms)	-183.54 ± 23.55	-176.99 ± 18.25

Table 1. Mean ± 1 SE APA magnitude and timing during the maximal exertion pulls under the No Threat and Threat condition. Asterisk indicates statistical significance between conditions ($p \leq 0.05$).

4.3 Scaling of APA Magnitude to Force Exertion

Postural threat did not alter the scaling of preparatory EMG activity relative to pulling force. The slope of the MG EMG amplitude vs. pulling force regression line was 0.099 ±

0.049 μV/N and 0.285 ± 0.144 μV/N for the No Threat and Threat conditions, respectively (T = 96.5, p = 0.344). The slope between SOL EMG amplitude and force exertion was 0.059 ± 0.009 μV/N and 0.066 ± 0.011 μV/N for the No Threat and Threat conditions, respectively ($t(18)$ = -0.592, p = 0.561). The slope between HAM EMG amplitude and force exertion was 0.127 ± 0.009 μV/N for the No Threat and 0.057 ± 0.011 μV/N for the Threat condition (T = 98.5, p = 0.887) (Figure 6).

In contrast to the EMG data, postural threat altered the scaling of COP displacement relative to pulling force ($t(18)$ = 2.59, p = 0.019, d = -0.45). Participants demonstrated a 22.3% smaller change in COP displacement per unit of force exertion during the Threat (0.016 ± 0.002 cm/N) compared to the No Threat (0.020 ± 0.002 cm/N) condition. Scatter plots and regression lines for each participant can be found in Appendix III. However, the scaling of peak COP velocity with pulling force was not different between the No Threat (0.077 ± 0.017 cm/s/N) and Threat (0.075 ± 0.015 cm/s/N) conditions (T = 99.0, p = 0.872) (Figure 6).

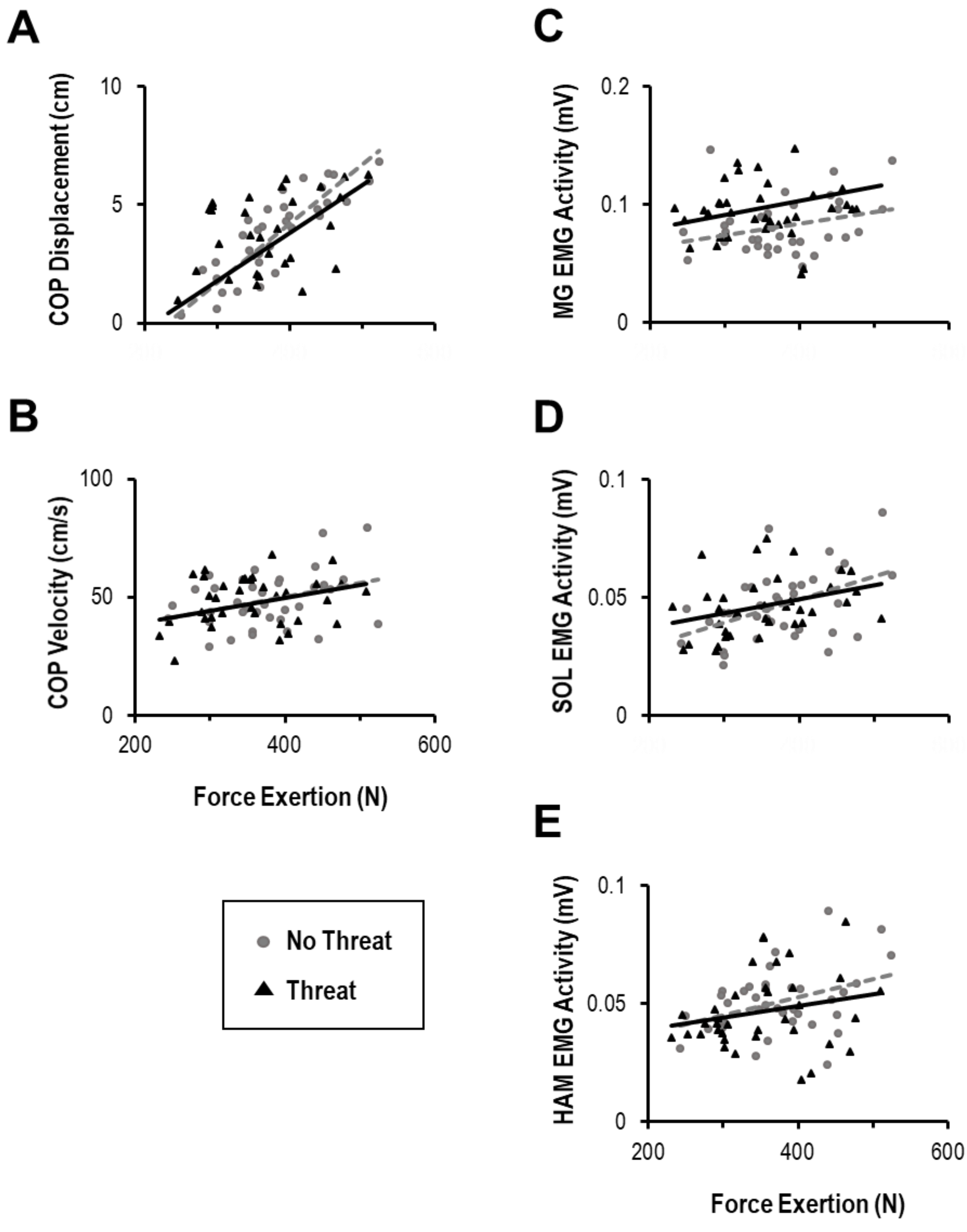


Figure 6. The relationship between each APA magnitude measure (A, COP displacement at force onset; B, peak COP displacement velocity; C, MG EMG amplitude; D, SOL EMG amplitude; and E, HAM EMG amplitude) and pulling force during the No Threat (grey) and Threat (black) conditions for a single participant. The dashed and solid lines represent the regression line between each dependent measure and pulling force for the No Threat and Threat conditions, respectively.

Postural threat did not influence the strength of the relationship between the dependent measures reflecting APA magnitude and pulling force. For all slopes, the correlation coefficient r, and amount of shared variability R^2 were not different with or without postural threat (Table 2).

		No Threat	Threat	Statistical Analysis
MG x Force	r	0.159 ± 0.062	0.146 ± 0.042	$t(18) = 0.244$, $p = 0.810$
	R^2	9.44 ± 3.30 %	5.34 ± 1.71 %	$T = 82.0$, $p = 0.601$
SOL x Force	r	0.301 ± 0.039	0.309 ± 0.042	$t(18) = -0.141$, $p = 0.890$
	R^2	11.86 ± 2.66 %	12.76 ± 2.41 %	$T = 99.0$, $p = 0.872$
HAM x Force	r	0.276 ± 0.077	0.335 ± 0.062	$T = 107.5$, $p = 0.615$
	R^2	18.04 ± 3.59 %	18.16 ± 4.09 %	$T = 86.0$, $p = 0.717$
COP displacement x Force	r	0.631 ± 0.079	0.557 ± 0.054	$T = 70.0$, $p = 0.314$
	R^2	42.52 ± 4.84 %	36.16 ± 4.69 %	$t(18) = 1.28$, $p = 0.216$
Peak COP velocity x Force	r	0.392 ± 0.066	0.346 ± 0.050	$t(18) = 0.596$, $p = 0.558$
	R^2	23.11 ± 4.70 %	16.40 ± 3.94 %	$T = 70.0$, $p = 0.314$

Table 2. The mean ± 1 SD strength of the relationship (r) and the amount of shared variability (R^2) between the dependent (MG, SOL, HAM, COP displacement, peak COP velocity) and independent (pulling force) variables for the No threat and Threat conditions. None of these measures were different between conditions.

4.4 Scaling of APA Timing to Force Exertion

Postural threat affected the scaling of MG EMG onset to pulling force ($t(18) = -2.116$, $p = 0.049$, $d = 0.76$). Participants demonstrated a 36.7% smaller change in MG EMG onset per unit of force exertion during the Threat condition (-0.306 ± 0.060 ms/N) compared to the No Threat condition (-0.484 ± 0.054 ms/N). However, there were no differences in the scaling of SOL and HAM EMG onset, as well as COP onset, to pulling force with postural threat (Figure 7). The slope of the regression line between SOL EMG onset and pulling force was -0.407 ± 0.060 ms/N and -0.274 ± 0.046 ms/N for the No Threat and Threat conditions, respectively (T = 139, p = 0.077). The slope for HAM EMG onset vs. pulling force was -0.266 ± 0.058 ms/N and -0.131 ± 0.038 ms/N for the No Threat and Threat conditions, respectively (t(18) = -1.936, p = 0.069). Lastly, the slope between COP onset and pulling force was not significantly different between the No Threat (-0.489 ± 0.063 ms/N) and the Threat (-0.403 ± 0.075 ms/N) conditions (T = 133, p = 0.126) (Figure 7). Scatter plots and regression lines for each participant can be found in Appendix III.

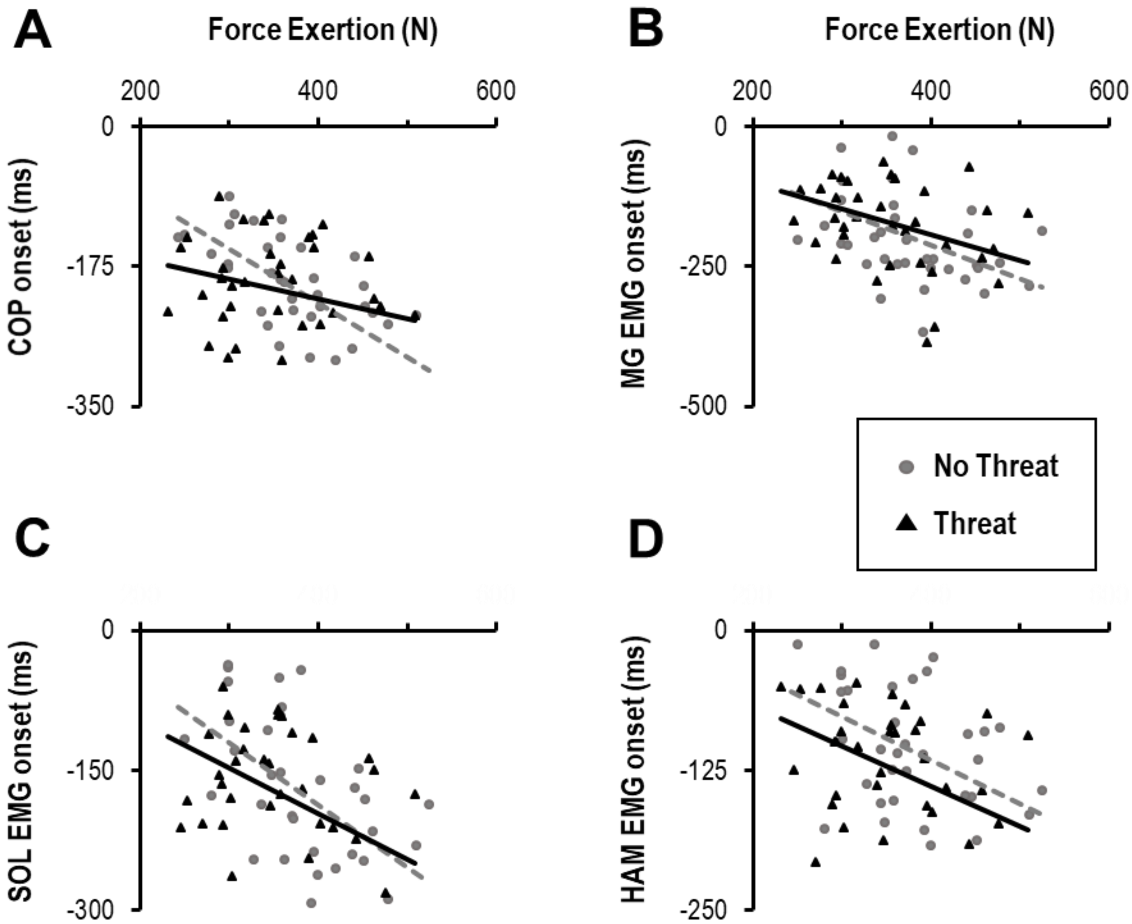


Figure 7. The slopes between APA timing measures (A, COP onset; B, MG EMG onset; C, SOL EMG onset; D, HAM EMG onset) and pulling force during the No Threat (grey) and Threat (black) conditions for a single participant. COP and EMG onsets are relative to pulling force onset, with a negative onset latency indicating a change in COP or EMG prior to pulling force onset.

Postural threat influenced the strength of the relationship between SOL EMG onset and pulling force. There was a weaker relationship between SOL EMG onset and pulling force, as reflected by a 33% smaller r value ($t(18) = -2.273$, $p = 0.036$, $d = 0.35$) and 56% smaller R^2 value ($T = 46.0$, $p = 0.049$, $r = -0.45$) during the Threat compared to the No Threat condition. For all other dependent measures, the correlation coefficient and amount of shared variability did not change between conditions (Table 3).

		No Threat	**Threat**	**Statistical Analysis**
MG onset x Force	r R^2	-0.448 ± 0.039 22.77 ± 3.71 %	-0.291 ± 0.067 16.49 ± 3.59 %	$t(18) = -2.006$, $p = 0.060$ $T = 68.0$, $p = 0.277$
SOL onset x Force	r R^2	-0.393 ± 0.046 19.24 ± 3.32 %	-0.262 ± 0.045 10.57 ± 2.39 %	$t(18) = -2.273$, $p = 0.036$ ***** $T = 46.0$, $p = 0.049$ *****
HAM onset x Force	r R^2	-0.243 ± 0.058 12.06 ± 2.72 %	-0.159 ± 0.048 6.64 ± 2.05 %	$t(18) = -1.308$, $p = 0.207$ $T = 57.0$, $p = 0.126$
COP onset x Force	r R^2	-0.429 ± 0.041 21.37 ± 3.54 %	-0.346 ± 0.057 17.73 ± 4.70 %	$t(18) = -1.59$, $p = 0.129$ $T = 78.0$, $p = 0.494$

Table 3. The mean ± 1 SE strength of the relationship (r) and the amount of shared variability (R^2) between the dependent measures (EMG or COP onset) and pulling force. Asterisks indicate statistical significance between conditions ($p \leq 0.05$).

5.0 Discussion

Previous research has established that postural threat modulates the generation of APAs during movements executed at maximal speed or exertion (Gendre et al., 2016; Phanthanourak et al., 2016; Yiou et al., 2011; Adkin et al., 2002). The purpose of this thesis was to investigate whether a threat-related response evoked by the risk of a M-L surface translation affects an individual's ability to scale APA magnitude and timing across a range of forces. The results of this study suggest that postural threat has some influence on the ability to scale APA magnitude to the amount of force exertion. This was evidenced by the more homogenous COP displacements over the measured range of forces during the postural threat condition. However, in contrast to the hypothesis, the reduced scaling of APA magnitude was not accompanied by a parallel change in the scaling of SOL, MG, and HAM muscle activity. Similarly, no changes in the scaling of COP onset to force were observed with postural threat.

5.1 Postural Threat Effect on Physiological Arousal and Psycho-social Factors

The surface translation paradigm used in this study elicited the desired threat-related response (i.e., increased physiological arousal, perceived anxiety and fear of falling, and decreased balance confidence). However, it is important to note that the amount of change was not as large as those previously reported (Adkin et al., 2002; Phanthanourak et al., 2016). For example, Phanthanourak et al. (2016) used a similar surface translation paradigm while participants completed a heel raise task and observed larger changes to skin conductance (54% compared to the 14% increase in this study), perceived fear of falling (55% vs. 46% increase) and anxiety (60% vs. 29% increase). Similarly, when Adkin et al. (2002) presented postural threat by having individuals complete a heel raise task at the edge of an elevated surface, larger changes in skin conductance (63% increase), perceived balance confidence (46% decrease) and anxiety (77% increase) were reported.

Several factors may explain why the participants of this study did not perceive the postural threat to be as threatening as in previous studies. First, standing at an elevated height, where there is no physical perturbation to the body, is a drastically different postural threat paradigm than being physically propelled off balance by a surface translation. Further, while participants in the current study had ample room on the platform to regain their balance during the handle pull task, Adkin et al. (2002) had participants complete a heel raise task at the edge of the platform to prevent them from taking a compensatory step in the event of a forward fall. Thus, the need to be more cautious due to a restricted step area may have resulted in the larger threat response. In fact, when individuals completed the heel raise further away from the surface edge (i.e., able to take a forward step if needed), participants demonstrated significantly smaller changes in skin conductance, and perceived balance confidence and anxiety (Adkin et al., 2002). As the consequences associated with experiencing a loss of balance are greater with step restriction (Brown et al., 2006), the conditions where individuals had the ability to take a stabilizing step may have been viewed as less threatening.

When comparing the work of Phanthanourak et al. (2016) to the current study, both of which utilized a M-L support surface translation to induce postural threat, it is likely that differences in the speed and acceleration of the surface translations between studies account for differences in the size of the threat-related response. Specifically, Phanthanourak et al. (2016) used surface translations that were 0.9 m/s in peak velocity and 1.7 m/s^2 in peak acceleration, while the current study's translations were 0.7 m/s in peak velocity and 1.6 m/s^2 in peak acceleration. The faster surface translations may have led to a larger threat-related response, as the changes to postural control are known to scale to the amount of postural threat (Adkin et al., 2000).

Task differences may also account for differences in the size of the threat-related response. Both Adkin et al. (2002) and Phanthanourak et al. (2016) had participants rise as quickly and as far forward onto their toes as possible (i.e., heel raise task). This requires individuals to move from a more stable posture, standing with a larger BOS and lower COM (Pollock et al., 2000), to a less stable posture over the toes, where the BOS was smaller and the COM was higher. In contrast, participants in the current study pulled onto a stationary handle device with varying amounts of force exertion and induced no change in BOS size and COM height. Thus, the more destabilizing movement associated with a heel raise may have led to the larger threat-related responses observed by Adkin et al. (2002) and Phanthanourak et al. (2016).

5.2 Postural Threat Effect on APAs during Maximal Force Exertion

Previous studies have shown that postural threat influences anticipatory postural control during movements requiring maximal speed or exertion (Adkin et al., 2002; Gendre et al., 2016; Phanthanourak et al., 2016; Yiou et al., 2011). Accordingly, the healthy young adults in this study executed under-sized APA responses during the maximum exertion trials when compared to the non-threatening condition.

Participants in this study were found to exert 5.8% larger pulling forces during the maximal pulling trials when postural threat was present. The magnitude of this threat-related effect on movement execution is similar to the findings of Schmidt et al. (2009), where individuals presented with arousing photos, independent of valence, demonstrated ~6% larger maximal force exertion during a hand grip task. Although participants in the current study executed larger and thus more destabilizing movements in the presence of postural threat, the more forceful pulls were not preceded by larger or earlier stabilizing APAs. This was evidenced by the lack of differences in the COP onsets, displacements and velocities between the maximal pull trials of the No Threat and Threat conditions. Further, although larger pulls were executed during the Threat condition, HAM EMG activity actually decreased by 54.6% and MG EMG onset occurred 12.1% later with postural threat.

In the study conducted by Phanthanourak et al. (2016), individuals also executed larger movements, as reflected by faster heel raises, with postural threat. However, the larger and faster heel raises that occurred with postural threat were accompanied by larger APAs. This contrasting result may be explained by the different tasks under investigation. For a heel raise task, larger heel raise movements cannot occur without larger and faster peak backward COP displacements, as the destabilizing APA ensures that the COM is propelled up and forward over the toes (Adkin et al., 2002; Kasai & Kawai, 1994; Massion, 1992). In contrast, individuals can generate a higher force when pushing or pulling, without a concomitant increase in the stabilizing APA but stability will be compromised (Kubicki et al., 2015; Lee et al., 2015; Weeks, 1994).

5.3 Postural Threat Effect on the Scaling of APA Magnitude and Timing

Not all individuals are able to appropriately scale APAs in magnitude or timing to an upcoming postural disturbance. If feelings of elevated anxiety, increased fear of falling, and reduced balance confidence are responsible for this decreased ability to scale APAs, it was hypothesized that young adults would demonstrate less scaling of APAs in the presence of postural threat. In partial support of the hypothesis, a reduced ability to scale the magnitude, and to a lesser extent the timing, of APAs to pulling force was observed during the Threat compared to the No Threat condition.

When postural threat was present, participants demonstrated more homogenous MG EMG onsets relative to increasing force exertion. However, changes in scaling were limited to this muscle as there were no differences in the scaling of HAM and SOL EMG onsets to force exertion with postural threat. Since the observed decline in scaling of MG EMG onset relative to pulling force did not lead to a change in the scaling of COP onset with postural threat, it is probable that changes in the ability to scale MG EMG onset to force exertion were of minimal functional consequence.

Compared to the modest changes with respect to the scaling of APA timing, there was a more noticeable reduction in the individuals' ability to scale APA magnitude to pulling force during the Threat compared to the No Threat condition. This decrease appears to be a result of more homogenous COP displacements at pulling onset with increasing force exertion (i.e., smaller slopes) compared to when the threat was absent. This under-sized APA response when greater postural stabilization is required is similar to responses generated by older adults, who tend to "under-respond" in situations of large internal postural disturbance, such as pushing and pulling at greater forces (Błaszczyk et al., 1997).

Consequently, the findings of this study might suggest that the impaired ability to generate larger and earlier APAs with more forceful movements, as demonstrated by older adults and individuals with neurological disorders (Elble & Leffler, 2000; Kanekar & Aruin, 2014; Kubicki et al., 2015; Lee et al., 2015; Pereira et al., 2014; Ustinova et al., 2004; Weeks, 1994), could in part be due to elevated feelings of anxiety or fear of falling.

The more homogenous COP displacements with varying pulling forces observed with postural threat were not a result of reduced scaling of activity of the posterior leg muscles. No changes in MG, SOL, and HAM EMG activity were observed with threat. Instead, this decline in the scaling of COP displacement, but not with posterior leg muscle activity, could have arisen as a result of an increase in co-activation at the ankle, knee, or hip joints. A greater level of muscle co-activation would lead to a stiffer control of posture, which is a strategy that is often adopted when experiencing postural threat (Brown et al., 2006; Carpenter et al., 2006; Carpenter et al., 2001) or increased postural instability (Krishnamoorthy, Latash, Scholz & Zatsiorsky, 2004; Piscitelli, Falaki, Solnik & Latash, 2017). A stiffening or increased co-activation at the ankle joint during the generation of APAs is also often observed in older adults and has been suggested to account for the inefficient APAs demonstrated by older adults (Kanekar & Aruin, 2014; Kubicki et al., 2015; Lee et al., 2015). Thus, the more destabilizing conditions (i.e., risk of experiencing M-L surface translations) of the current study may have led to co-contraction during the generation of APAs, resulting in the reduced scaling of APA magnitude observed with postural threat. However, this can only be speculated as TA EMG activity was not collected during the current study. Future work should include EMG measures from the anterior leg muscles to confirm whether increased co-contraction and a joint stiffening strategy contributes to the declines in the scaling of APAs to an impending disturbance to balance.

A possible mechanism that could explain the reduced scaling of APA magnitude under postural threat is that individuals shifted to a more conscious control of posture

(Huffman et al., 2009; Johnson et al., 2017; Masters, 1992; Pijpers et al., 2005; Zaback et al., 2016). Based on the "conscious processing hypothesis," when individuals experience an increase in arousal, and specifically anxiety, they attempt to consciously control or "reinvest" in otherwise automatic movements. This movement reinvestment could lead individuals to revert to postural control strategies used when they were first learning a skill (Masters, 1992; Pijpers et al., 2005). This could explain why the homogenous APA magnitudes that occur under postural threat are similar to APAs that are generated by individuals who are initially learning how to complete upper limb movements at varying speeds and with varying loads (Aimola, Santello, Grua & Casabona, 2011; Fine & Thoroughman, 2007; Pienciak-Siewert, Horan & Ahmed, 2016; Piscitelli et al., 2017). Specifically, when young adults first learn to perform a reaching task at various speeds, they execute similar-sized APAs that are ideal for the mean or medium-sized disturbances to balance (Fine & Thoroughman, 2007; Pienciak-Siewert et al., 2016). However, this causes the APA to be over-sized in situations involving slow speeds (minimal disturbances) and under-sized during faster speeds (larger disturbances) (Aimola et al., 2011; Fine & Thoroughman, 2007; Pienciak-Siewert et al., 2011; Piscitelli et al., 2017). While the APA strategy appears to be similar in these two situations (i.e., learning a skill vs. postural threat), future studies should consider incorporating the Movement Specific Reinvestment Scale (Huffman et al., 2009) to confirm whether a shift to a more conscious control of posture can explain the threat-related effect on the scaling of APAs.

6.0 Limitations, Future Directions, and Conclusions

6.1 Limitations and Future Directions

Although increases in feelings of anxiety and fear of falling were observed with postural threat, not all participants (n=3) demonstrated an increase in physiological arousal during the Threat compared to the No Threat condition. Differences in the physiological response to the postural threat may have been due to individual differences among participants, such as whether participants had trait anxiety, trait movement reinvestment, or previous experience with moving surfaces (Zaback et al., 2015). Furthermore, it is likely that over time, at least some of the participants habituated to the inflexible characteristics of the surface translations. This would have resulted in participants finding the postural threat to be less threatening as the experimental trials progressed. To address this issue, future analyses could eliminate any trials where a participant was no longer threatened (i.e., had an EDA that had returned to the No Threat level) during the Threat condition. This would ensure that any changes between the No Threat and Threat groups of trials would truly be due to a threat-related response (i.e., increased physiological arousal, anxiety, and fear of falling).

Another limitation of the current study was the assumption that the scaling of APA magnitude and timing to force exertion were linearly related. Although the strength and the amount of shared variability of the relationships were strong, it is possible that the slope of the regression line may have depended on the range of forces being exerted. For example, some individuals could have demonstrated a stronger scaling effect (i.e., steeper slope) when pulling within the 50 to 75 % Fmax range, but a weaker effect (i.e., smaller slope) when they pulled from 75 to 100% Fmax. To further eliminate some of the limitations associated with analyzing regression lines, it may be better to match for and sort between set levels of force exertion between the No Threat and Threat conditions. This would allow for the comparison of APA characteristics at specific force levels between the two conditions.

Finally, it is important to note that while the participants in this study demonstrated declines in their ability to scale APA magnitude to force exertion with threat, the amount of change was small when compared to the difference in scaling between older and young adults (Błaszczyk et al., 1997). Thus, it would be worth determining how much an elevated physiological arousal, anxiety, and fear of falling, and reduced balance confidence contribute to older adults' reduced ability to scale APA magnitude and timing.

6.2 Conclusion

When healthy young adults were presented with a postural threat in the form of M-L surface translations, they were more physiologically aroused, anxious, fearful of falling, as well as less confident in their balance abilities. As a result of this threat-related response, individuals produced smaller APAs where increased postural stabilization was required (i.e., when pulling at maximal exertion). Postural threat also resulted in young adults having a reduced ability to scale the APA magnitude to the amount of disturbance to balance. The findings of this study suggest that increased physiological arousal, anxiety and fear of falling and reduced balance confidence, prevalent in older adults, may contribute to the reductions in APA scaling demonstrated by older adults.

References

Adkin, A. L., Frank, J. S., Carpenter, M. G., & Peysar, G. W. (2000). Postural control is scaled to level of postural threat. *Gait & posture*, *12*(2), 87-93.

Adkin, A. L., Frank, J. S., Carpenter, M. G., & Peysar, G. W. (2002). Fear of falling modifies anticipatory postural control. *Experimental brain research*,*143*(2), 160-170.

Aimola, E., Santello, M., La Grua, G., & Casabona, A. (2011). Anticipatory postural adjustments in reach-to-grasp: effect of object mass predictability. *Neuroscience letters*, *502*(2), 84-88.

Balasubramaniam, R., & Wing, A. M. (2002). The dynamics of standing balance. *Trends in cognitive sciences*, *6*(12), 531-536.

Belenkii, V. Y., Gurfinkel, V.S., & Paltsev, Y. I. (1967). Elements of control of voluntary movements. *Biofizika*, *12*(1), 135-141.

Błaszczyk, J. W., Lowe, D. L., & Hansen, P. D. (1997). Age-related differences in performance of stereotype arm movements: movement and posture interaction. *Acta neurobiologiae experimentalis*, *57*(1), 49-57.

Bleuse, S., Cassim, F., Blatt, J. L., Labyt, E., Derambure, P., Guieu, J. D., & Defebvre, L. (2006). Effect of age on anticipatory postural adjustments in unilateral arm movement. *Gait & posture*, *24*(2), 203-210.

Blickhan, R., Ernst, M., Koch, M., & Müller, R. (2013). Coping with disturbances. *Human movement science*, *32*(5), 971-983.

Brown, L. A., Polych, M. A., & Doan, J. B. (2006). The effect of anxiety on the regulation of upright standing among younger and older adults. *Gait & posture*, *24*(4), 397-405.

Carpenter, M. G., Adkin, A. L., Brawley, L. R., & Frank, J. S. (2006). Postural, physiological and psychological reactions to challenging balance: Does age make a difference. *Age and ageing*, *35*(3), 298-303.

Carpenter, M. G., Frank, J. S., Silcher, C. P., & Peysar, G. W. (2001). The influence of postural threat on the control of upright stance. *Experimental brain research*, *138*(2), 210-218.

Cordo, P. J., & Nashner, L. M. (1982). Properties of postural adjustments associated with rapid arm movements. *Journal of neurophysiology*, *47*(2), 287-302.

Cram, J.R., & Kasman, G.S. (2010). *Introduction to Surface Electromyography*. E. Criswell (Ed.). Canada: Jones and Bartlett Publishers.

Davis, J. R., Campbell, A. D., Adkin, A. L., & Carpenter, M. G. (2009). The relationship between fear of falling and human postural control. *Gait & posture*, *29*(2), 275-279.

Dietz, V., Kowalewski, R., Nakazawa, K., & Colombo, G. (2000). Effects of changing stance conditions on anticipatory postural adjustment and reaction time to voluntary arm movement in humans. *The Journal of physiology*, *524*(2), 617-627.

Dunlap, W. P., Cortina, J. M., Vaslow, J. B., & Burke, M. J. (1996). Meta-analysis of experiments with matched groups or repeated measures designs.

Elble, R. J., & Leffler, K. (2000). Pushing and pulling with the upper extremities while standing: the effects of mild Alzheimer dementia and Parkinson's disease. *Movement disorders*, *15*(2), 255-268.

Field, A. (2013). *Discovering statistics using IBM SPSS statistics*. Sage.

Fine, M. S., & Thoroughman, K. A. (2007). Trial-by-trial transformation of error into sensorimotor adaptation changes with environmental dynamics. *Journal of neurophysiology*, *98*(3), 1392-1404.

Friedli, W. G., Cohen, L., Hallett, M., Stanhope, S., & Simon, S. R. (1988). Postural adjustments associated with rapid voluntary arm movements. II. Biomechanical analysis. *Journal of Neurology, Neurosurgery & Psychiatry*, *51*(2), 232-243.

Gendre, M., Yiou, E., Gélat, T., Honeine, J. L., & Deroche, T. (2016). Directional specificity of postural threat on anticipatory postural adjustments during lateral leg raising. *Experimental brain research*, *234*(3), 659-671.

Ghasemi, A., & Zahediasl, S. (2012). Normality tests for statistical analysis: A guide for non-statisticians. *International journal of endocrinology and metabolism*, *10*(2), 486-489.

Hadjistavropoulos, T., Delbaere, K., & Fitzgerald, T. D. (2011). Reconceptualizing the role of fear of falling and balance confidence in fall risk. *Journal of Aging and Health*, *23*(1), 3-23.

Huffman, J. L., Horslen, B. C., Carpenter, M. G., & Adkin, A. L. (2009). Does increased postural threat lead to more conscious control of posture. *Gait & posture*, *30*(4), 528-532.

Johansson, R., Magnusson, M., & Akesson, M. (1988). Identification of human postural dynamics. *IEEE Transactions on Biomedical Engineering*, *35*(10), 858-869.

Johnson, K. J., Zaback, M., Tokuno, C. D., Carpenter, M. G., & Adkin, A. L. (2017). Exploring the relationship between threat-related changes in anxiety, attention focus, and postural control. *Psychological research*, 1-14.

Kanekar, N., & Aruin, A. S. (2014). The effect of aging on anticipatory postural control. *Experimental brain research*, *232*(4), 1127-1136.

Kasai, T., & Kawai, K. (1994). Quantitative EMG analysis of analysis of anticipatory postural adjustments of voluntary contraction of leg muscles in standing man. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *93*(3), 184-187.

Krishnamoorthy, V., Latash, M. L., Scholz, J. P., & Zatsiorsky, V. M. (2004). Muscle modes during shifts of the center of pressure by standing persons: effect of instability and additional support. *Experimental brain research*, *157*(1), 18-31.

Kubicki, A., Mourey, F., & Bonnetblanc, F. (2015). Balance control in aging: Improvements in anticipatory postural adjustments and updating of internal models. *BMC geriatrics*, *15*(1), 162.

Lee, W. A., Michaels, C. F., & Pai, Y. C. (1990). The organization of torque and EMG activity during bilateral handle pulls by standing humans. *Experimental Brain Research*, *82*(2), 304-314.

Lee, Y. J., Chen, B., & Aruin, A. S. (2015). Older adults utilize less efficient postural control when performing pushing task. *Journal of Electromyography and Kinesiology*, *25*(6), 966-972.

Legters, K. (2002). Fear of falling. *Physical therapy*, *82*(3), 264.

Maki, B. E., Holliday, P. J., & Topper, A. K. (1991). Fear of falling and postural performance in the elderly. *Journal of gerontology*, *46*(4), M123-M131.

Massion, J. (1992). Movement, posture and equilibrium: interaction and coordination. *Progress in neurobiology*, *38*(1), 35-56.

Masters, R. S. (1992). Knowledge, knerves and know-how: The role of explicit versus implicit knowledge in the breakdown of a complex motor skill under pressure. *British journal of psychology*, *83*(3), 343-358.

Mochizuki, G., Ivanova, T. D., & Garland, S. J. (2004). Postural muscle activity during bilateral and unilateral arm movements at different speeds. *Experimental brain research*, *155*(3), 352-361.

Pereira, S., Silva, C. C., Ferreira, S., Silva, C., Oliveira, N., Santos, R., ... & Correia, M. V. (2014). Anticipatory postural adjustments during sitting reach movement in post-stroke subjects. *Journal of electromyography and kinesiology*, *24*(1), 165-171.

Petersen, T. H., Rosenberg, K., Petersen, N. C., & Nielsen, J. B. (2009). Cortical involvement in anticipatory postural reactions in man. *Experimental brain research*, *193*(2), 161.

Pienciak-Siewert, A., Horan, D. P., & Ahmed, A. A. (2016). Trial-to-trial adaptation in control of arm reaching and standing posture. *Journal of neurophysiology*, *116*(6), 2936-2949.

Phanthanourak, A. L., Cleworth, T. W., Adkin, A. L., Carpenter, M. G., & Tokuno, C. D. (2016). The threat of a support surface translation affects anticipatory postural control. *Gait & Posture*, *50*, 145-150.

Pijpers, J. R., Oudejans, R. R., & Bakker, F. C. (2005). Anxiety-induced changes in movement behaviour during the execution of a complex whole-body task. *The Quarterly Journal of Experimental Psychology Section A*, *58*(3), 421-445.

Piscitelli, D., Falaki, A., Solnik, S., & Latash, M. L. (2017). Anticipatory postural adjustments and anticipatory synergy adjustments: preparing to a postural perturbation with predictable and unpredictable direction. *Experimental brain research*, *235*(3), 713-730.

Pollock, A. S., Durward, B. R., Rowe, P. J., & Paul, J. P. (2000). What is balance. *Clinical rehabilitation*, *14*(4), 402-406.

Rogers, M. W., Kukulka, C. G., & Soderberg, G. L. (1992). Age-related changes in postural responses preceding rapid self-paced and reaction time arm movements. *Journal of gerontology*, *47*(5), M159-M165.

Rosenthal, R. (1991). *Meta-analytic procedures for social research* (Vol. 6). Sage.

Schmidt, L., Cléry-Melin, M. L., Lafargue, G., Valabrègue, R., Fossati, P., Dubois, B., & Pessiglione, M. (2009). Get aroused and be stronger: emotional facilitation of physical effort in the human brain. *Journal of Neuroscience*, *29*(30), 9450-9457.

Shaw, J. A., Stefanyk, L. E., Frank, J. S., Jog, M. S., & Adkin, A. L. (2012). Effects of age and pathology on stance modifications in response to increased postural threat. *Gait & posture*, *35*(4), 658-661.

Smith, R. E., Smoll, F. L., & Schutz, R. W. (1990). Measurement and correlates of sport-specific cognitive and somatic trait anxiety: The Sport Anxiety Scale. *Anxiety research*, *2*(4), 263-280.

Stegeman, D. F., & Hermens, H. (2007). Standards for surface electromyography: The European project Surface EMG for non-invasive assessment of muscles (SENIAM). *Enschede: Roessingh Research and Development*, 108-12.

Stelmach, G. E., Populin, L., & Müller, F. (1990). Postural muscle onset and voluntary movement in the elderly. *Neuroscience letters*, *117*(1), 188-193.

Sturnieks, D. L., Delbaere, K., Brodie, M. A., & Lord, S. R. (2016). The influence of age, anxiety and concern about falling on postural sway when standing at an elevated level. *Human movement science*, *49*, 206-215.

Sturnieks, D. L., George, R. St., & Lord, S. R. (2008). Balance disorders in the elderly. *Neurophysiologie Clinique/Clinical Neurophysiology*, *38*(6), 467-478.

Takacs, J., Carpenter, M. G., Garland, S. J., & Hunt, M. A. (2013). The role of neuromuscular changes in aging and knee osteoarthritis on dynamic postural control. *Aging and disease*, *4*(2), 84-99.

Tinetti, M. E., & Powell, L. (1993). Fear of falling and low self-efficacy: A cause of dependence in elderly persons. *Journal of gerontology*.

Ustinova, K. I., Goussev, V. M., Balasubramaniam, R., & Levin, M. F. (2004). Disruption of coordination between arm, trunk, and center of pressure displacement in patients with hemiparesis. *Motor control*, *8*(2), 139-159.

Weeks, D. L. (1994). Age-related differences in temporal scaling of postural EMG activity. *Aging Clinical and Experimental Research*, *6*(5), 323-333.

Woollacott, M. H., & Manchester, D. L. (1993). Anticipatory postural adjustments in older adults: Are changes in response characteristics due to changes in strategy. *Journal of gerontology*, *48*(2), M64-M70.

Yiou, E., Deroche, T., Do, M. C., & Woodman, T. (2011). Influence of fear of falling on anticipatory postural control of medio-lateral stability during rapid leg flexion. *European journal of applied physiology*, *111*(4), 611-620.

Zaback, M., Carpenter, M. G., & Adkin, A. L. (2016). Threat-induced changes in attention during tests of static and anticipatory postural control. *Gait & posture*, *45*, 19-24.

Zaback, M., Cleworth, T. W., Carpenter, M. G., & Adkin, A. L. (2015). Personality traits and individual differences predict threat-induced changes in postural control. *Human movement science*, *40*, 393-409.

Appendix I – Fear of Falling Questionnaire

Please answer the following questions (by indicating the percentage on the right) about how you honestly feel towards/felt performing the handle pull task during this surface condition using the following scale:

1. **Please rate how confident you are that you can maintain your balance and avoid a fall while performing the handle pull task.**

0	. . . .	**50**	. . . .	**100**	
I do not feel confident at all		I feel moderately confident		I feel completely confident	________

2. **Please rate how fearful of falling you felt when performing the handle pull task.**

0	. . . .	**50**	. . . .	**100**	
I did not feel fearful at all		I felt moderately fearful		I felt extremely fearful	________

Appendix II – State Anxiety Questionnaire

Please answer the following questions about how you honestly felt *while performing the handle pull task during this surface condition* using the following scale:

1	2	3	4	5	6	7	8	9
I did not feel this at all				I felt this moderately				I felt this extremely

1. **I felt nervous when completing the handle pulls.**

   1 2 3 4 5 6 7 8 9

2. **I had lapses of concentration when completing the handle pulls.**

   1 2 3 4 5 6 7 8 9

3. **I had self-doubts when completing the handle pulls.**

   1 2 3 4 5 6 7 8 9

4. **I felt myself tense and shaking when completing the handle pulls.**

   1 2 3 4 5 6 7 8 9

5. **I was concerned about being unable to concentrate when completing the handle pulls.**

   1 2 3 4 5 6 7 8 9

6. **I was concerned about completing the handle pulls correctly when standing on this surface.**

   1 2 3 4 5 6 7 8 9

7. **My body was tense when completing the handle pulls.**

   1 2 3 4 5 6 7 8 9

8. **I had difficulty focusing on what I had to do when completing the handle pulls.**

   1 2 3 4 5 6 7 8 9

9. I was worried about my personal safety when completing the handle pulls.

1 2 3 4 5 6 7 8 9

10. I felt my stomach sinking when completing the handle pulls.

1 2 3 4 5 6 7 8 9

11. While trying to complete the handle pulls, I didn't pay attention to the screen in front of me all of the time.

1 2 3 4 5 6 7 8 9

12. My heart was racing when completing the handle pulls.

1 2 3 4 5 6 7 8 9

13. Thoughts of falling interfered with my concentration during the handle pull task.

1 2 3 4 5 6 7 8 9

14. I was concerned that others would be disappointed with my performance on the handle pull task.

1 2 3 4 5 6 7 8 9

15. I found myself hyperventilating when completing the handle pulls.

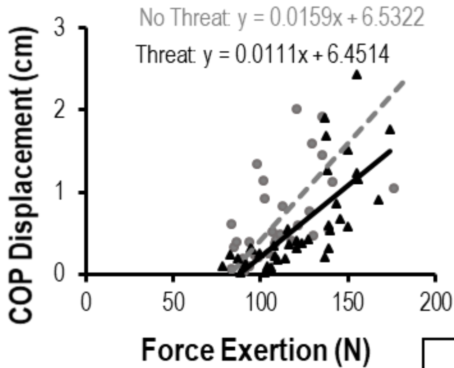
1 2 3 4 5 6 7 8 9

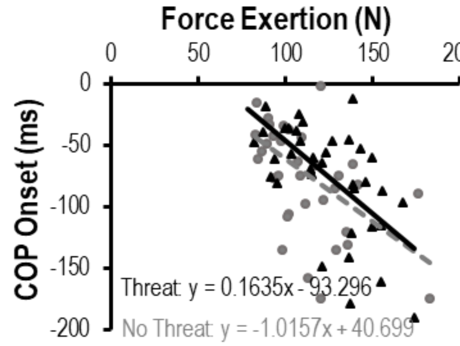
16. I found myself thinking about things not related to doing the handle pull task.

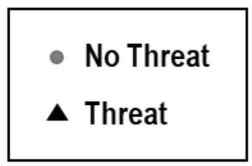
1 2 3 4 5 6 7 8 9

Appendix III – Individual Participant Data: COP Scaling

Subject 1







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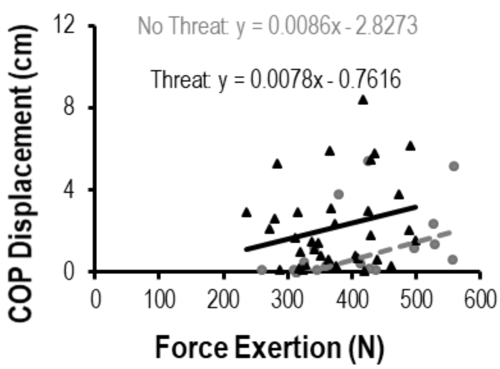

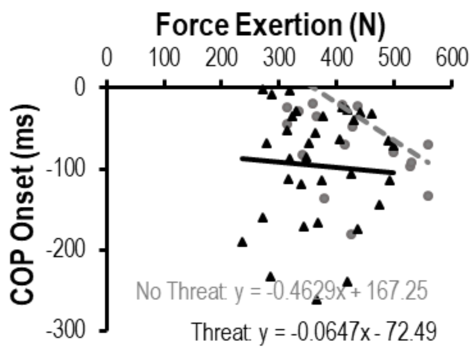

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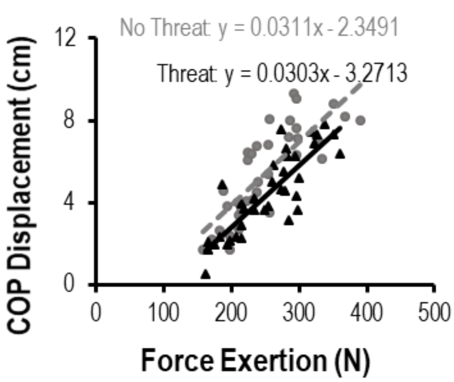
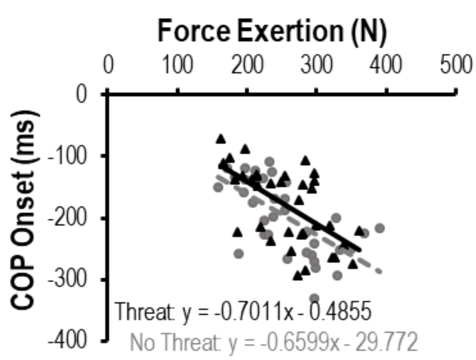
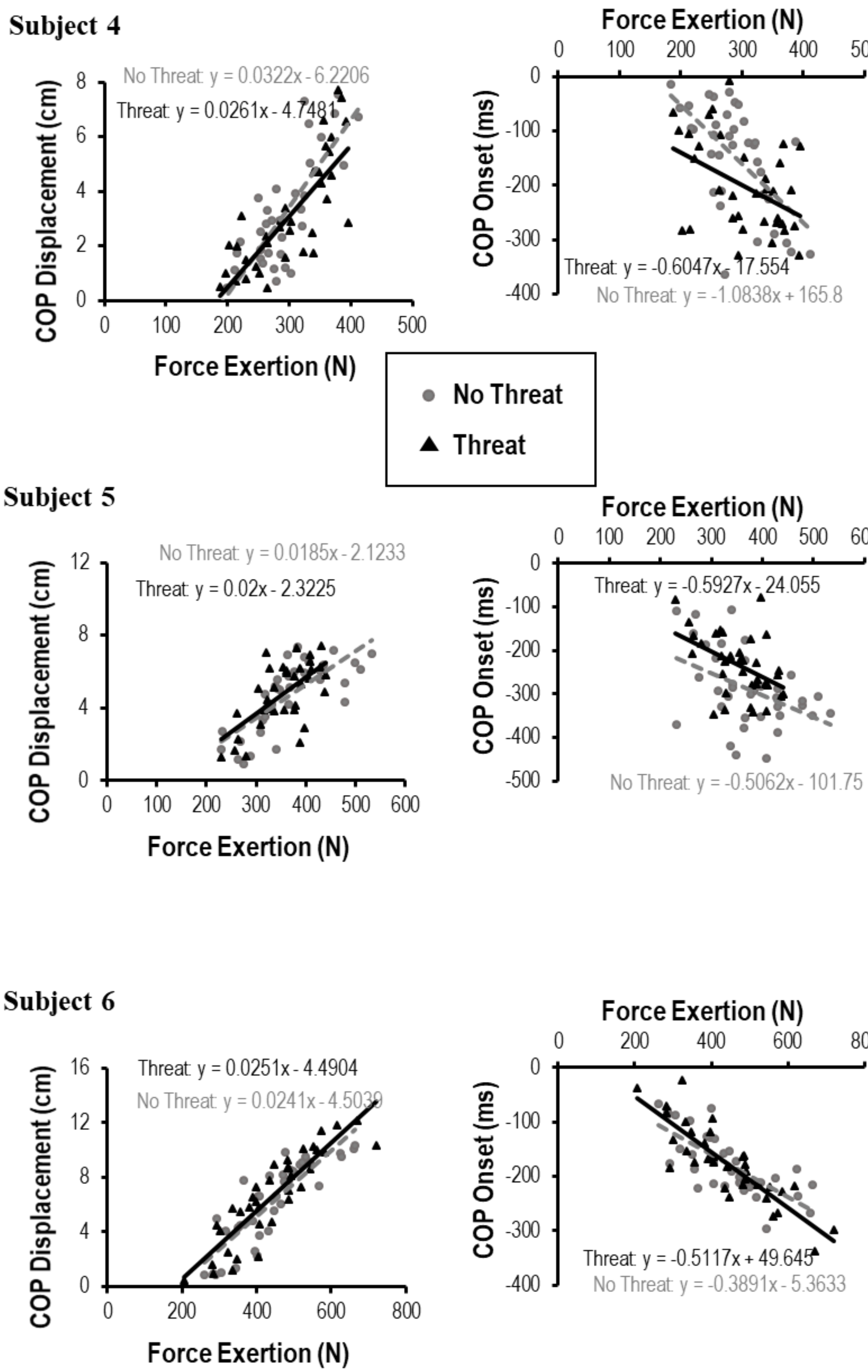
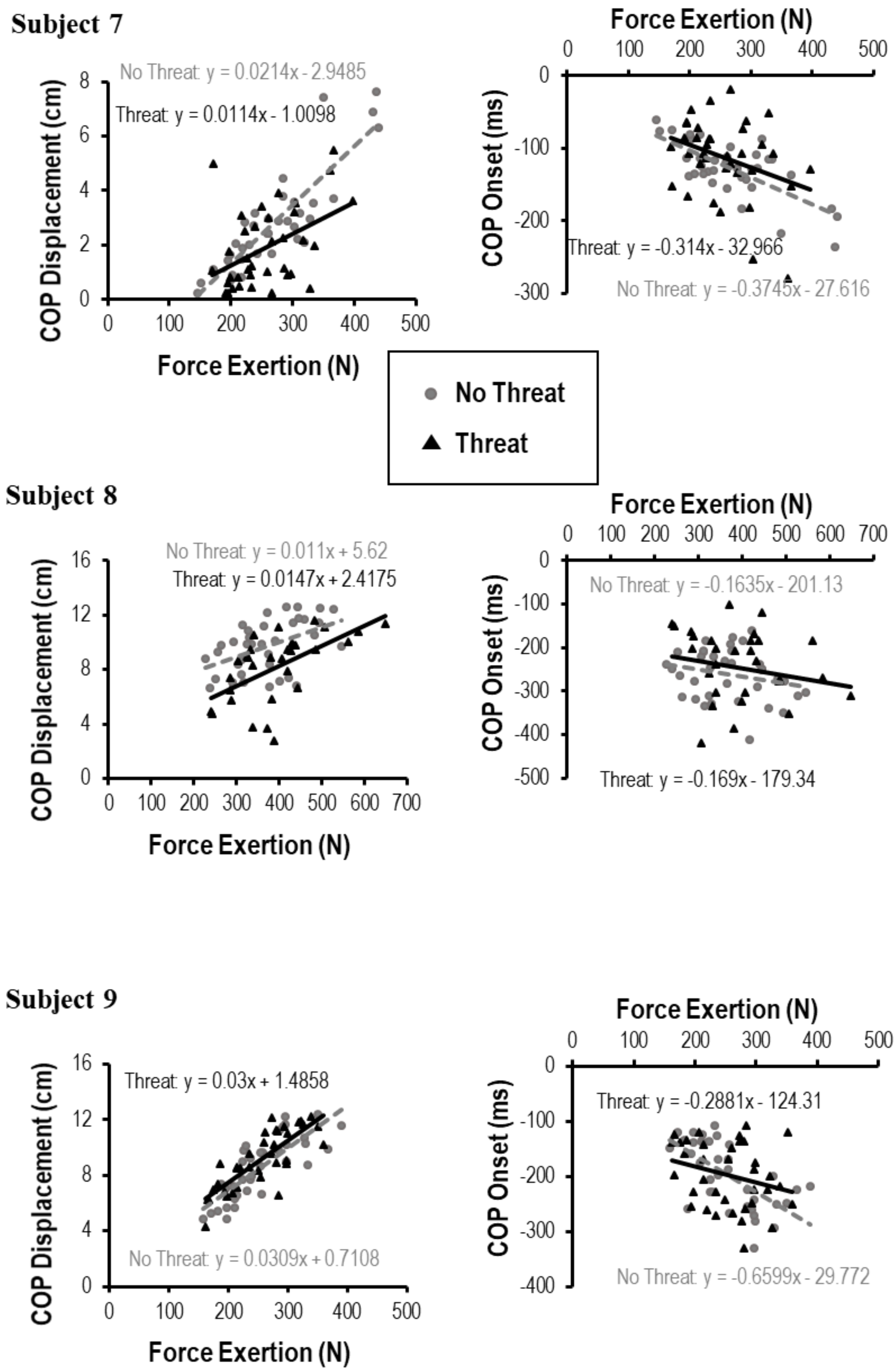
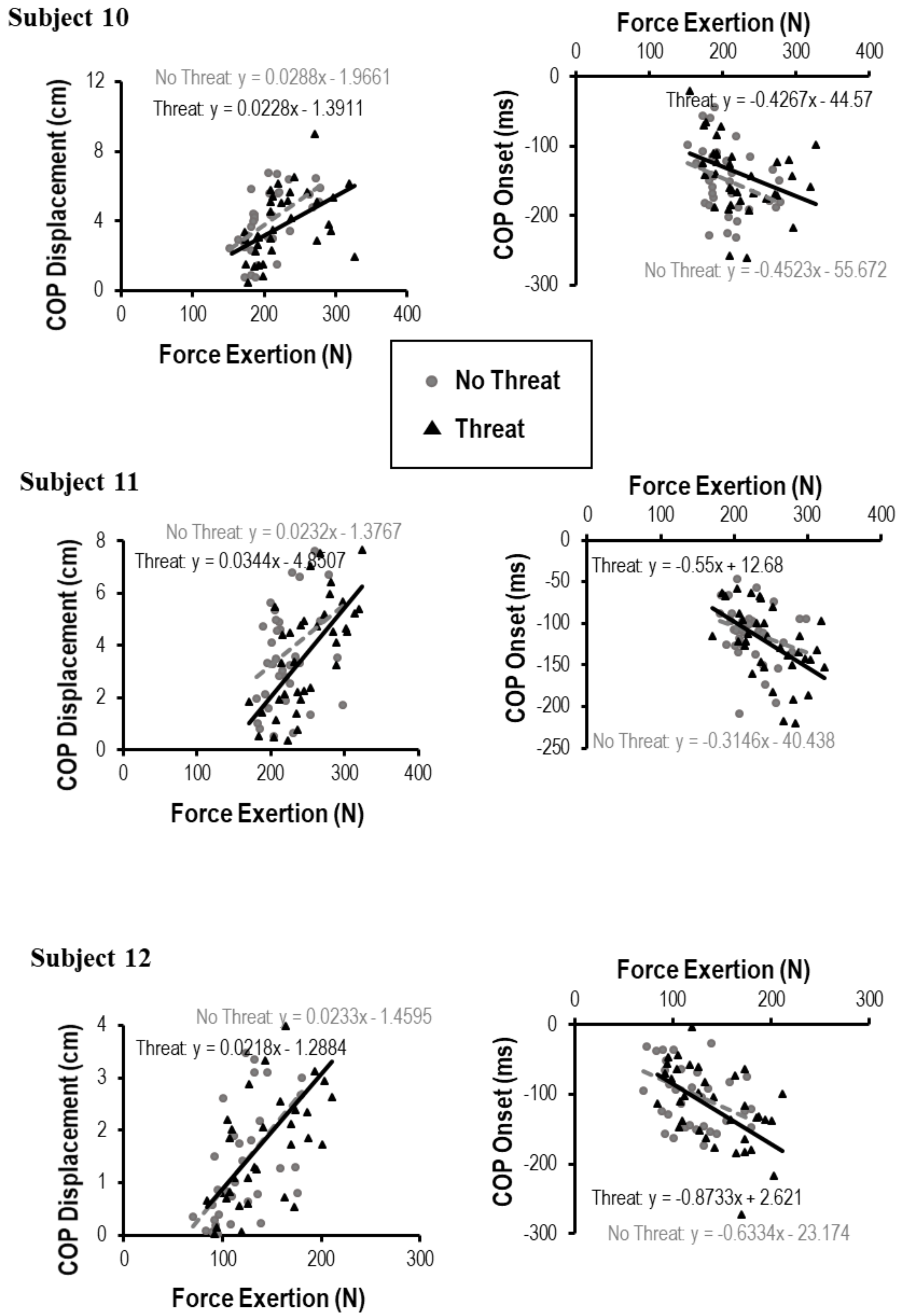
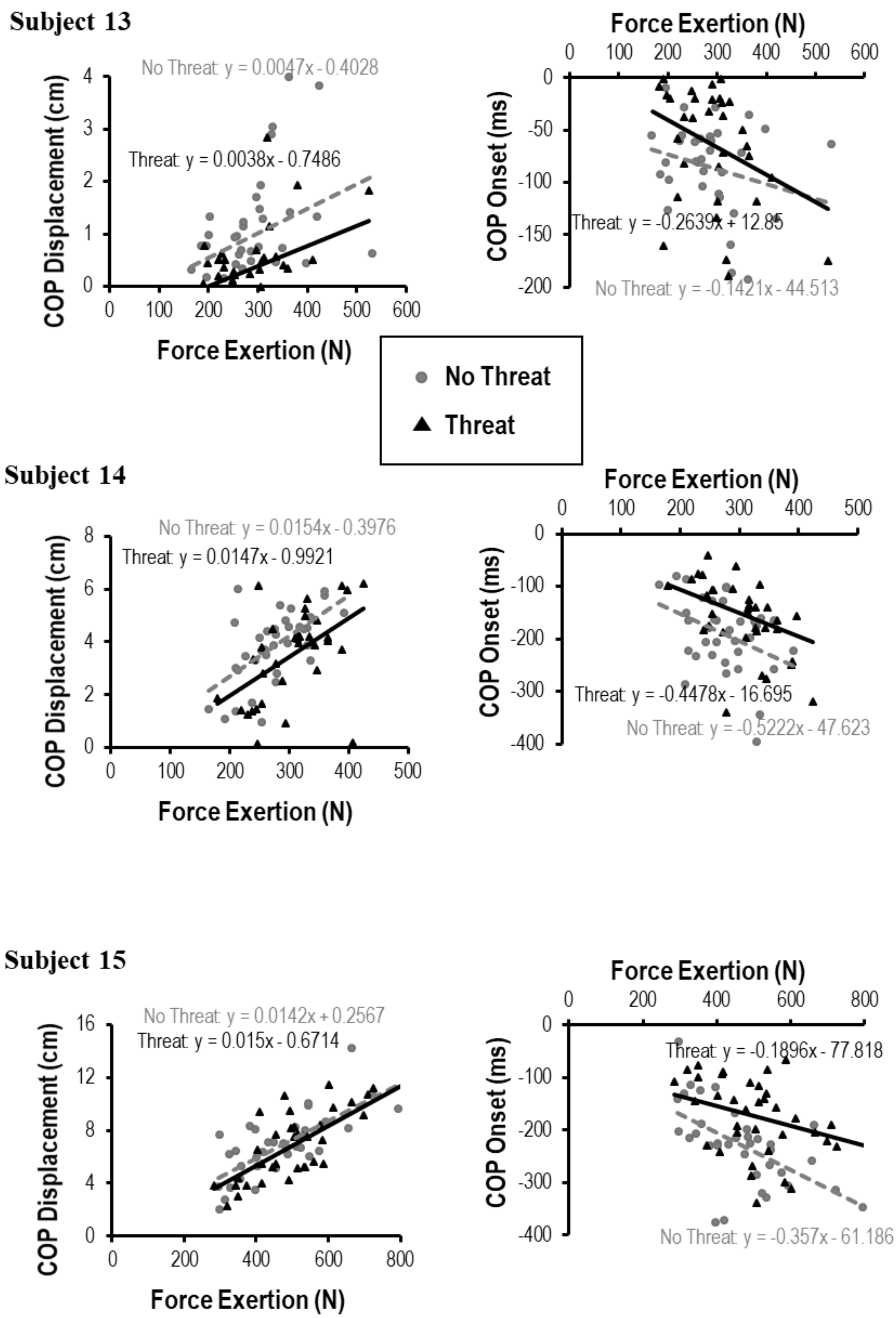


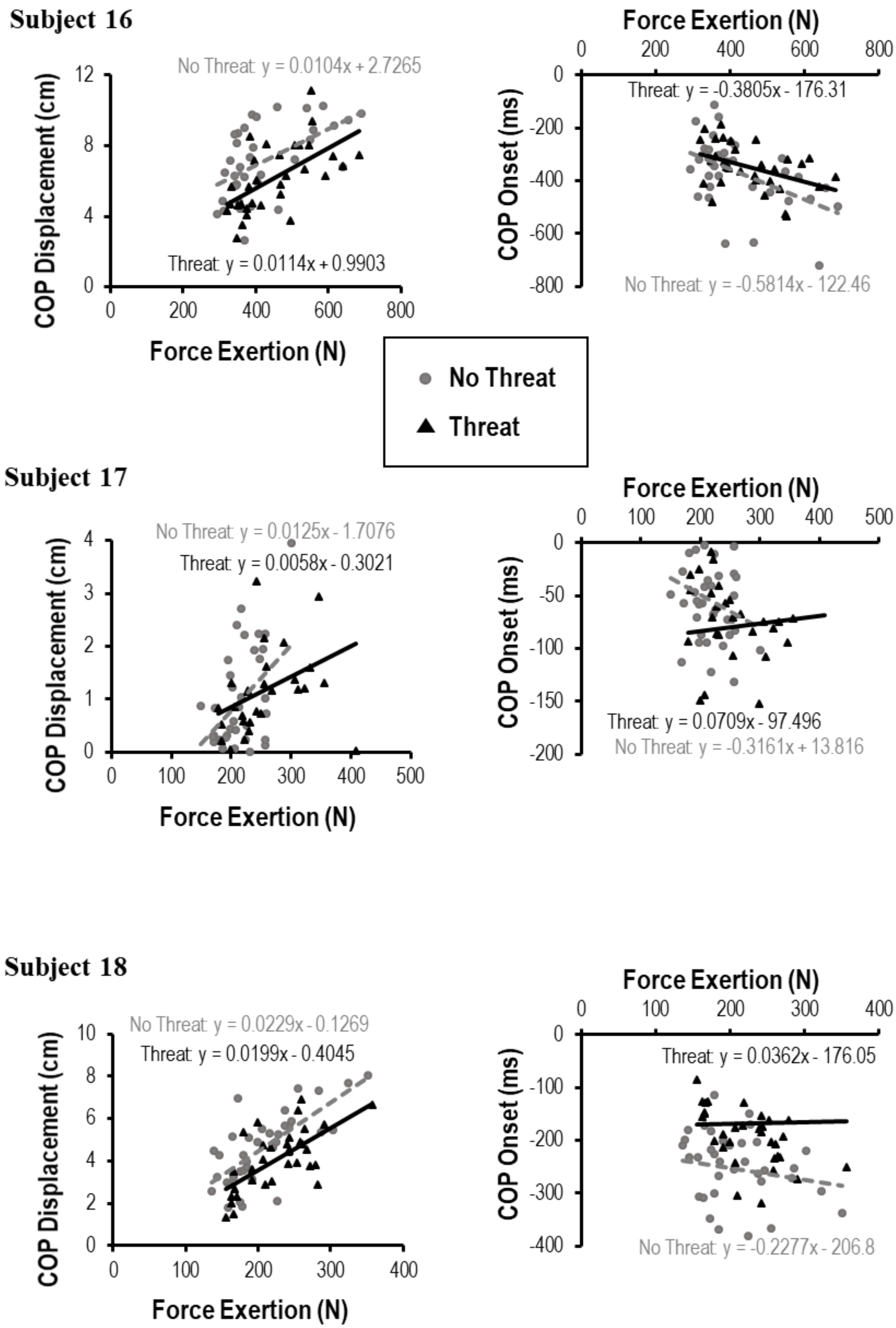


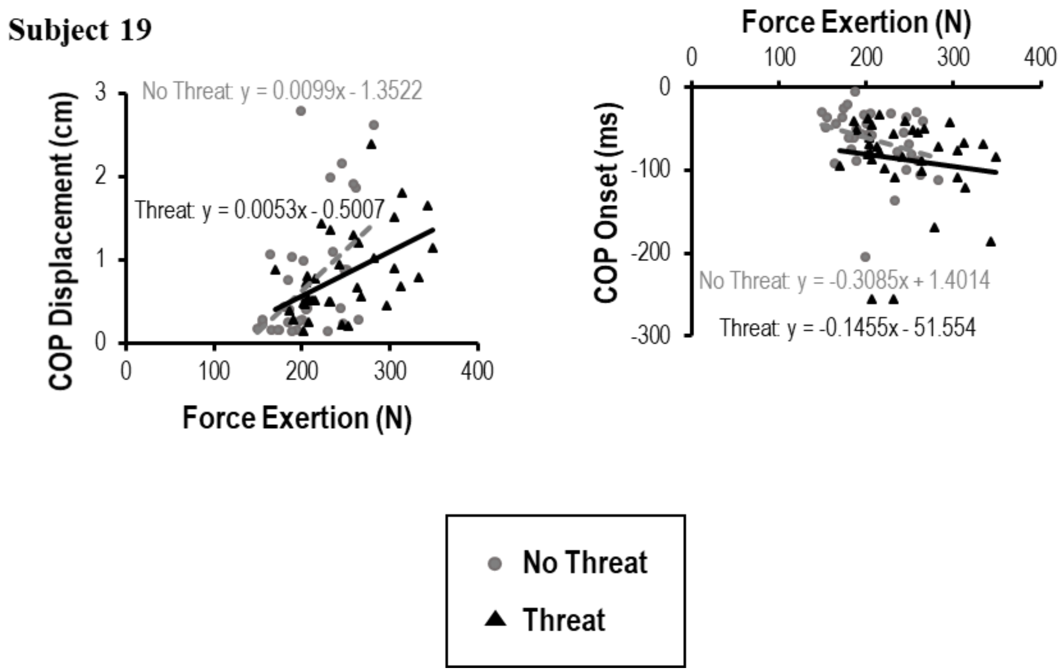

Subject 4
No Threat y = 0.0322x - 6.2206
Threat y = 0.0261x - 4.7481
COP Displacement (cm)
Force Exertion (N)
Force Exertion (N)
COP Onset (ms)
Threat y = -0.6047x - 17.554
No Threat y = -1.0838x + 165.8
No Threat
Threat
Subject 5
No Threat y = 0.0185x - 2.1233
Threat y = 0.02x - 2.3225
COP Displacement (cm)
Force Exertion (N)
Force Exertion (N)
COP Onset (ms)
Threat y = -0.5927x - 24.055
No Threat y = -0.5062x - 101.75
Subject 6
Threat y = 0.0251x - 4.4904
No Threat y = 0.0241x - 4.5039
COP Displacement (cm)
Force Exertion (N)
Force Exertion (N)
COP Onset (ms)
Threat y = -0.5117x + 49.645
No Threat y = -0.3891x - 5.3633


Subject 7
No Threat y = 0.0214x - 2.9485
Threat y = 0.0114x - 1.0098
COP Displacement (cm)
Force Exertion (N)
Force Exertion (N)
COP Onset (ms)
Threat y = -0.314x - 32.966
No Threat y = -0.3745x - 27.616
No Threat
Threat
Subject 8
No Threat y = 0.011x + 5.62
Threat y = 0.0147x + 2.4175
COP Displacement (cm)
Force Exertion (N)
Force Exertion (N)
COP Onset (ms)
No Threat y = -0.1635x - 201.13
Threat y = -0.169x - 179.34
Subject 9
Threat y = 0.03x + 1.4858
No Threat y = 0.0309x + 0.7108
COP Displacement (cm)
Force Exertion (N)
Force Exertion (N)
COP Onset (ms)
Threat y = -0.2881x - 124.31
No Threat y = -0.6599x - 29.772


Subject 10
No Threat y = 0.0288x - 1.9661
Threat y = 0.0228x - 1.3911
COP Displacement (cm)
Force Exertion (N)
Threat y = -0.4267x - 44.57
No Threat y = -0.4523x - 55.672
COP Onset (ms)
No Threat
Threat
Subject 11
No Threat y = 0.0232x - 1.3767
Threat y = 0.0344x - 4.8507
Threat y = -0.55x + 12.68
No Threat y = -0.3146x - 40.438
Subject 12
No Threat y = 0.0233x - 1.4595
Threat y = 0.0218x - 1.2884
Threat y = -0.8733x + 2.621
No Threat y = -0.6334x - 23.174


Subject 13
No Threat y = 0.0047x - 0.4028
Threat y = 0.0038x - 0.7486
COP Displacement (cm)
Force Exertion (N)
Force Exertion (N)
COP Onset (ms)
Threat y = -0.2639x + 12.85
No Threat y = -0.1421x - 44.513
No Threat
Threat
Subject 14
No Threat y = 0.0154x - 0.3976
Threat y = 0.0147x - 0.9921
COP Displacement (cm)
Force Exertion (N)
Force Exertion (N)
COP Onset (ms)
Threat y = -0.4478x - 16.695
No Threat y = -0.5222x - 47.623
Subject 15
No Threat y = 0.0142x + 0.2567
Threat y = 0.015x - 0.6714
COP Displacement (cm)
Force Exertion (N)
Force Exertion (N)
COP Onset (ms)
Threat y = -0.1896x - 77.818
No Threat y = -0.357x - 61.186


Subject 16
No Threat y = 0.0104x + 2.7265
Threat y = 0.0114x + 0.9903
COP Displacement (cm)
Force Exertion (N)
Threat y = -0.3805x - 176.31
No Threat y = -0.5814x - 122.46
COP Onset (ms)
No Threat
Threat
Subject 17
No Threat y = 0.0125x - 1.7076
Threat y = 0.0058x - 0.3021
Threat y = 0.0709x - 97.496
No Threat y = -0.3161x + 13.816
Subject 18
No Threat y = 0.0229x - 0.1269
Threat y = 0.0199x - 0.4045
Threat y = 0.0362x - 176.05
No Threat y = -0.2277x - 206.8


Subject 19
No Threat: y = 0.0099x - 1.3522
Threat: y = 0.0053x - 0.5007
COP Displacement (cm)
Force Exertion (N)
Force Exertion (N)
COP Onset (ms)
No Threat: y = -0.3085x + 1.4014
Threat: y = -0.1455x - 51.554
No Threat
Threat